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Project Report DCA-7

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Technology Assessment for Future MILSATCOM Systems: An Update of the EHF Bands

1 October 1980

Prepared for the Defense Communications Agency
under Electronic Systems Division Contract F19628-80-C-0002 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Raymond L. Loiselle

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TECHNOLOGY ASSESSMENT FOR FUTURE MILSATCOM SYSTEMS: AN UPDATE OF THE EHF BANDS

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LEXINGTON MASSACHUSETTS

ABSTRACT

Severe crowding of the radio frequency spectrum and of the geostationary orbital arc, coupled with DoD requirements for increased bandwidth, impel the transition of future MILSATCOM systems to operating frequencies between 20 and 50 GHz (EHF). The development of the systems architecture and transitional strategy are the current focus of DCA/MSO studies. This report, prepared in support of the DCA/MSO, assesses the technology necessary to support MILSATCOM evolution to EHF.

The technology assessment delineates the current and projected availabilities of critical MILSATCOM subsystems. In addition, the equally critical issues of producibility, reliability and cost are addressed. To provide a basis for these issues, a qualitative assessment is presented of the limits, frequency dependence and implementation of EHF technology, the commercial availability of components and test equipment in these bands, and the production base at EHF. The emphasis in the subsystem assessment is directed toward the high power amplifier (HPA) which has been identified as the most costly and critical subsystem. Toward that end, traveling wave tube amplifiers (TWTAs) and solid-state amplifiers (SSAs) are assessed for both the ground and space segments. These assessments encompass potential suppliers, current commercial availability, producibility and reliability, and development efforts and projections. As rain attenuation at EHF impacts system design and technology requirements, a refined global rain attenuation model is provided. Finally, recommendations are presented for technology development efforts and further studies to support EHF MILSATCOM deployment.

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I. INTRODUCTION

1.1 Background

Current U. S. MILSATCOM systems operate in the UHF (200-400 MHz) and SHF (8/7 GHz) bands. These frequency bands are shared on a global basis with terrestrial systems, as well as with the satellite services of other nations. The concomitant frequency- and orbital-congestion problems are severe and will worsen with the worldwide increase in the demand for telecommuncations. Coincident with this saturation of the radio frequency spectrum and geostationary orbital arc, are the growing requirements within the DoD for increased bandwidth*. The projected demands for increased capacity include the need for greater bandwidth to accommodate higher data rates for wideband users and increased numbers of circuits for mobile users. These projected user requirements cannot be adequately satisfied at UHF and SHF. In addition, significant bandwidth requirements stem from the longstanding, unsatisfied need for anti-jam (AJ) protection for MILSATACOM users, particularly for small mobile terminals. The AJ limitations of small terminals in the UHF band have long been recognized, as well as the need to move to higher frequencies. As wide, contiguous bandwidth is fundamental to AJ spread-spectrum modulation, it is unlikely that adequate AJ protection can be provided in the SHF band.

These problems, increased requirements and unsatisfied needs of the MILSATCOM community present the DoD with two pressing issues: consideration of higher frequency bands for future systems; and selection of anti-jam modulation techniques for mobile users. To address these issues in depth, two ad hoc working groups were formed in early 1978. These two working groups were composed of representatives from the Military Departments, Defense Agencies and Federal Contract Research Centers, and met under DCA/MSO chairmanship. The findings of these working groups were published in

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*In the commercial SATCOM sector, the increasing demands for capacity portend a saturation at C-Band (6/4 GHz), and force an evolution to Ku-Band (14/11 Ghz) in the near term and EHF (30/20 GHz) in the far term.

February 1979 as MSO Technical Reports: "Final Report of the Working Group on Anti-Jam Modulation Systems for Mobile Users"; and "Final Report of the Working Group on Frequency Selection for Future MILSATCOM Systems". The MSO Frequency Selection Working Group assessed: the user requirements; the current and planned investment; the projected threat to MILSATCOM systems; the available and projected technology; and the systemic, operational and transitional concepts. (The previous technology assessment report[1], prepared in support of this working group, addressed the EHF technology issue.) The final report of the Frequency Selection Working Group placed in evidence those factors which support MILSATCOM evolution to EHF (i.e., capacity, AJ and LPI (Low Probability of Intercept)), and identified potential users of the EHF bands based on their current and projected unsatisfied needs.

Based on the results of the Working Groups, numerous MSO studies, and OSD and Congressional guidelines, the MSO issued, "A Framework for MILSATCOM Development" (FMD), a succinct architecture of plausible strategies for MILSATCOM system evolution. The evolution of the three-phase architecture is depicted in Fig. 1.1. The following material presents brief excerpts[2] from the FMD, relevant to the technology assessment task. The MSO points out in its FMD that, by the mid-80's, the DoD will have substantial space-segment resources embodied in the FLTSAT, LEASAT and DSCS-II/III satellites and in the AFSATCOM packages. In addition, this on-orbit satellite investment at UHF and SHF will be exceeded by the investment in earth terminals and associated user equipment. A pragmatic assessment of this financial investment coupled with the required shakedown cycle of the large earth terminal investment suggests slowing the rate of development and acquisition of space segments with completely new satellite designs, for the near term at least. (A new system for the nuclear-capable forces is probably an exception.) However, despite a pause in major new system acquisition, certain improvements (e.g., AJ service for WWMCCS and GMF, and additional capacity in several systems) are necessary, and should be implemented by block changes to existing systems. It then appears that aside from the significant upgrade in communications for nuclear-capable forces, and the correction of some other critical deficiencies, no

USER GROUPINGS	MILSATCOM SYSTEMS		
	NEAR TERM (1980-1985)	MID TERM (1985-1990)	FAR TERM (POST-1990)
Wideband	DSCS II	DSCS III	DSCS III-U
Mobile/Tactical	FLTSATCOM	LEASATCOM	TACSATCOM II
Nuclear-Capable	AFSATCOM	SSS	SSS-U

Fig. 1.1. MILSATCOM EVOLUTION

other new systems are needed until the late 80's. The intervening period should be used to lay a sound technical, production and pre-operational foundation for the next generation of satellite communications systems with enhanced military-unique properties. The FMD illuminates the need for vigorous, coordinated R&D programs within the Military Departments and Defense Agencies to define, develop, and test the advanced concepts and equipments for both the space and ground segments at EHF. In the absence of systemic or architectural focus, the Military Departments have initiated independent development programs in various aspects of the future systems. In the interest of converging these efforts, the MSO has prepared a "Technology Development Program Plan" (TDPP).

The TDPP defines a coordinated approach to the R&D required to insure the availability of the technology necessary to support future systems. Some of the objectives of the TDPP are: to minimize duplication of effort by coordination of programs; to mitigate the cost-risk and schedule-risk associated with the deployment of EHF MILSATCOMs; and, to insure an orderly, time-phased evolution to EHF with continuity of service. These objectives provide the guidance for and dictate the texture of this EHF technology assessment.

1.2 EHF Frequency Bands

The selection of higher frequency bands for MILSATCOM use is based on International and U.S. Government frequency allocations, available bandwidth, competing services, propagation effects, state of the technology and the unique communications needs of the DoD community. Table 1.1 lists the potential EHF bands for MILSATCOM use based on current U.S. frequency allocations for Government use. Also included in Table 1.1 are the recent rulings of GWARC-79 regarding these frequency bands. Note that the relevant changes instituted at WARC-79 are: the addition of Mobile-Satellite service as a primary service in the frequency bands 20.2-21.2 GHz (Space-to-Earth) and 30.0-31.0 GHz (Earth-to-Space), as proposed by the U.S.; the allocation of the frequency band 43.5-47.0 GHz (no designation) for Mobile-Satellite, Radionavigation-Satellite, Radio Navigation and Mobile services. In this

TABLE 1.1

CURRENT UNITED STATES GOVERNMENT FREQUENCY ALLOCATIONS
FOR EHF SATELLITE SERVICE

FREQUENCY BAND (GHz)	SERVICE ALLOCATION
20.2 - 21.2(1)	Fixed-Satellite Mobile-Satellite* (Space-to-Earth)
30.0 -31.0(1)	Fixed-Satellite Mobile-Satellite* (Earth-to-Space)
40.0 - 41.0(2)	Fixed-Satellite (Space-to-Earth)
43.5 - 47.0*	Mobile-Satellite* Sharing(3) not yet defined
50.0 - 51.0(2)	Fixed-Satellite (Earth-to-Space)

*WARC-79 allocation

(1) Exclusive Government service allocation.

(2) Shared with non-Government Fixed-Satellite and Mobile service.

(3) To be shared with Government Aeronautical and Maritime Mobile, Aeronautical and Maritime Radionavigation, and Aeronautical and Maritime Radionavigation-Satellite services; all services in this band to be shared with non-Government users.

latter frequency band, the U.S. proposal was to allocate 43.0-45.0 (Earth-to-Space) for Fixed-Satellite and Mobile-Satellite services (DoD), and 45.0 to 49.2 GHz for Radionavigation-Satellite, Mobile and Terrestrial services (DoT). The WARC allocation effectively combines the services proposed by the U.S. into one band, permits both Earth-to-Space and Space-to-Earth operation in that band, and reduces the bandwidth from 6.2 GHz to 3.5 GHz. The division of this current band (43.5-47.0 GHz) for U.S. Government service (i.e., DoD and DoT) has not yet been defined.

1.3 Technology Assessment Methodology

Technology assessment is one of the tasks conducted by Lincoln Laboratory in support of the DCA/MSO. The technology assessment task is directed toward defining the technology needed to support the deployment of future MILSATCOM systems. The technology assessment methodology (Fig. 1.2) first draws on existing MILSATCOM architectures and studies to develop "strawman" versions of these systems. The strawman systems are defined by frequency band leading to UHF, X-band, EHF, etc., strawman MILSATCOMs and corresponding technology assessments. From the operations requirements of the strawman system, the performance characteristics of the major subsystems are defined. In parallel with the characterization of the MILSATCOM system, a relevant technology base is established from a survey of operational systems, the current state-of-the-art, on-going research and development, and estimates and projections of future technology developments. Next, the strawman subsystem requirements are assessed vis-à-vis the technology data base to determine areas of deficiency. Finally, specific areas warranting research and development effort and for further study are delineated as input to the DCA/MSO technology development recommendations.

The previous technology assessment[1] addressed the capability of fundamental technology to provide a basis for the development of future EHF MILSATCOM systems. The critical issue being addressed was the potential level of performance that EHF technology could support. Consequently, the assessment drew heavily on developmental devices, laboratory demonstrations, studies and extrapolations. From that assessment, it was concluded that the technology base needed to support EHF MILSATCOMs was extant.

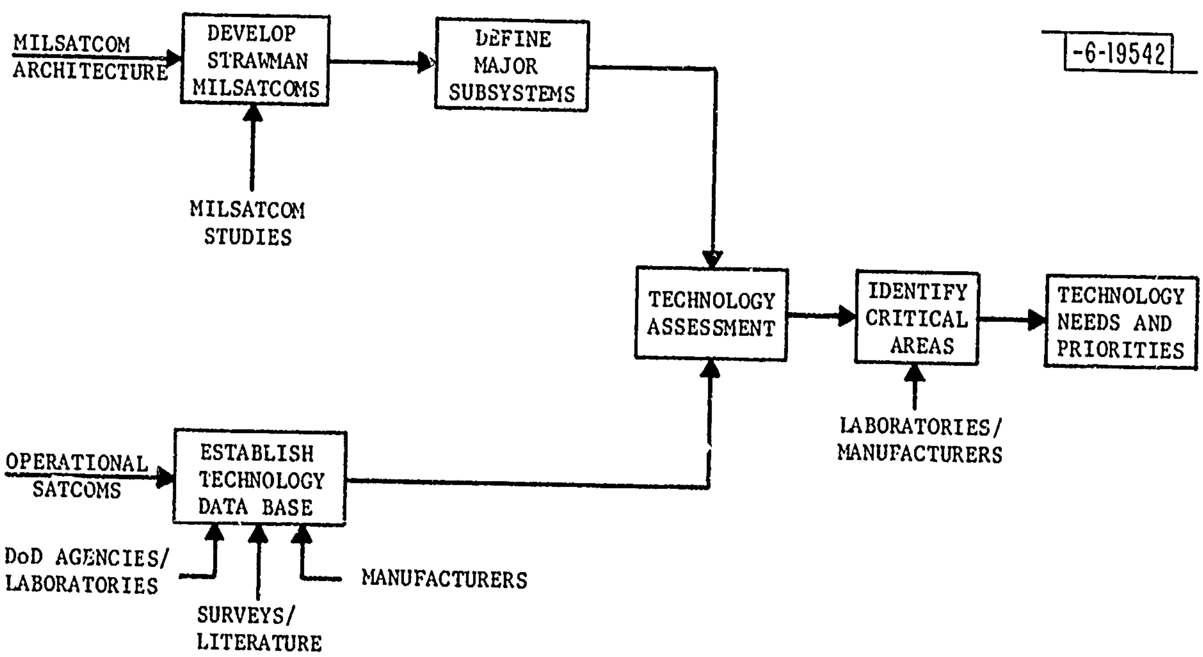

Fig. 1.2. Technology assessment methodology for future military communications satellite systems.

Subsequent to that assessment, the MSO FMD and TDPP have illuminated the need for technology development efforts directed toward minimizing the cost-risk and schedule-risk, and insuring the orderly, time-phased evolution to affordable EHF MILSATCOM systems. Additional critical technology issues then become: the level of EHF technology which is producible, reliable and affordable; and, the concomitant technology development efforts to bring about its exploitation. This assessment addresses these critical issues in addition to the basic capabilities of EHF technology. The goals of this assessment are to present in evidence the need for both device and production technology developments, and promote such developments equitably and in consonance.

1.4 Overview

To provide a basis for evaluating the critical issues of producibility, reliability and cost, Section II addresses: the limits, frequency dependence and implementation factors associated with EHF technology; the commercial availability of components and test equipment in these bands; and the current production base at EHF. As studies (Navy, DCA/MSO, LL) have indicated that the high power amplifier (HPA) is the most costly and critical subsystem in proposed EHF terminals, HPA technology is the focal point of this assessment. (Note that this assessment includes 60 GHz HPAs to support proposed satellite crosslinks.) Traveling wave tube amplifiers (TWTAs) are assessed in detail in Section III. This TWTA assessment first surveys the microwave tube market and potential suppliers; then examines the critical issues of producibility and cost vis-à-vis current technology and operating experience; on-going production technology development efforts and developments of alternative circuits are surveyed next; finally, TWT technology development efforts are recommended. Section IV assesses the alternative HPA technology, solid-state power devices. This assessment surveys viable generic devices, their current commercial availability, development efforts and projections, and power combining techniques, and concludes with appropriate device development recommendations. In Section V, a refined global rain attenuation estimation model is presented as an adjunct to current system studies. Finally, Section VI presents a summary of recommended technology development efforts and areas for further study.

II. EHF TECHNOLOGY AND INDUSTRIAL BASE

This section examines the limits, frequency dependence, and implementation factors associated with EHF technology, the commercial availability of components and test equipment in these bands, and the current production base at EHF. This assessment is both cursory and qualitative, but adequately serves its two-fold purpose: 1. to place in evidence the current state of the EHF industrial base to demonstrate the need for stimulation, capital investment and production development; 2. to compare the relative performance, risk and cost of exploiting the 30/20 versus the 45/40 GHz frequency bands* and thereby indicate the relative degree of difficulty and concomitant degree of effort required.

2.1 Technology Factors

The proposed evolution of MILSATCOM users to EHF will not be an en masse migration, but rather, will be restricted to those user communities whose current and projected needs cannot be satisfied at UHF or SHF. In an analogous manner, among the users selected for transition to EHF, some will realize adequate performance capabilities at 30/20 GHz; while others, having unique mission requirements, will obtain needed operational advantages at 45/20 GHz or 45/40 GHz. This section examines the technological factors that may enter into the frequency selection process, and that will indicate the areas needing more emphatic development effort. The technological factors addressed herein are the frequency limitations, frequency dependence and implementation factors associated with current EHF technology.

A. Frequency Limitations

Within the EHF band there are definite frequency limits on certain desired technology, the "desirability" stemming from improved performance and/or reduced cost compared to alternative technologies. Notable examples of such frequency-limited technology are low-noise and power FETs (Field Effect

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*This pairing of the uplink/downlink bands is for the purpose of comparison only, as will be evident later.

Transistors) for receiver and power amplifier applications, respectively. FETS offer potential performance advantages in both applications. FET LNAs (Low-Noise Amplifiers) offer both reductions in noise temperature compared to mixer front ends, and low-cost MIC (Microwave Integrated Circuit) fabrication. For solid-state HPAs*, FETs offer ease of combining and linear amplification compared to IMPATT diodes. Currently, FET technology provides attractive devices for both low-noise and high-power applications at 20 GHz. In the near term, this technology will be extended to 30 GHz and development efforts are on-going. Far term projections[1,3], predicated on significant advances in device and fabrication technology, indicate possible extension of FET technology to 40 GHz.

Another notable frequency limitation of EHF technology is the slow-wave circuit of the TWT** (Traveling Wave Tube) amplifier. The helical slow-wave circuit is less expensive than the coupled-cavity circuit typically used at EHF. The upper frequency limit for the helix circuit is obviously dependent upon the output power requirement. For ground terminal applications requiring output power > 100 W, the frequency limit is at or below 40 GHz for reliable, producible helix TWTs.

The frequency limitations of EHF technology are summarized in Table 2.1. Note that the exclusion of these technologies at 45/40 GHz does not deter operation in these bands, but does indicate the need for the further development of alternative technology to provide performance and cost comparable to the lower frequency devices.

B. Frequency Dependence

The frequency dependence of technology is difficult to quantify uniquely, primarily for two reasons. First, for some technology the frequency limits lie within or just above the EHF bands. Consequently, the functional representation of the degradation in performance with increasing frequency, F, is rapidly changing. Second, the impact of implementation factors (e.g.,

*Addressed in detail in Section IV.
**Addressed in detail in Section III.

TABLE 2.1

EHF TECHNOLOGY: FREQUENCY LIMITATIONS

TECHNOLOGY	ADVANTAGE	FREQUENCY LIMIT (GHz)
Low-Noise FET	Lower Noise than Mixer Low-Cost MIC Fabrication	$<$ 30 GHz (Near Term) $<$ 40 GHz (Far Term)
Power FET	Linear Amplification Easier Combining than IMPATT	$<$ 30 GHz (Near Term) $<$ 40 GHz (Far Term)
Helix TWT	1/5 to 1/3 the Cost of Coupled-Cavity TWT	$<$ 40 GHz ($P < 100$ W)

TABLE 2.2

EHF TECHNOLOGY: FREQUENCY DEPENDENCE

TECHNOLOGY	FREQUENCY DEPENDENCE	COMMENTS
Low-Noise Amplifiers Mixer Noise Temp. Paramp Noise Temp.	$T \alpha F^{1/2}$ $T \alpha F^{3/2}$	Frequency Limit on FETs
High-Power Amplifiers Solid State TWT	$PF^2 = C$ $PF^2 = C$ $PF^{8/3}$	Active Region Area $\alpha \lambda^2$ Electron Beam Area $\alpha \lambda^2$ Beam Voltage Constant
Rectangular Waveguide Attenuation	$A(dB) \alpha F^{3/2}$ $A(dB) \alpha F^{1/2}$	Constant Length Dimensions scaled with λ
Rain Attenuation	$A(dB) \alpha F^2$	Approximate

tighter tolerances, higher voltage and temperatures, etc.) are practically impossible to model. Therefore, the frequency dependence characteristics being presented herein are lower bounds, and are derived from simple scaling laws; the implementation factors are addressed in the following section.

The noise temperatures of mixer front ends and parametric amplifiers at EHF vary as $F^{1/2}$ and $F^{3/2}$, respectively. The FET LNA, while offering performance between these technologies at the lower end of the band, cannot be easily modeled as previously discussed. For power amplifiers, a simple scaling law is usually applied for both solid-state and TWT technology, i.e., PF^2 = Constant, where P = output power. Note that this relationship defines the limitation on output power. (These limits are delineated in Sections III and IV for TWT and solid-state amplifiers, respectively.) For solid-state devices, this relationship is derived from the active area being proportional to the square of the wavelength (λ^2). For TWT amplifiers (actually coupled-cavity circuits as the helix has frequency limits), the electron beam cross-sectional area scales as λ^2 (assuming a constant convergence ratio, i.e., ratio of cathode diameter to electron beam diameter). If the TWT beam voltage is held constant (e.g., due to limits on power supply technology), the output power decreases as $F^{8/3}$ (Refs. 4 and 5) rather than the F^2 assumed earlier.

The attenuation, A, in <u>dB</u> due to ohmic loss in dominant-mode rectangular waveguide is proportional to $F^{3/2}$ for a constant length (e.g., fixed separation between HPA and antenna in a transportable terminal). If all waveguide lengths are scaled with λ, as is typically the case in components, $A(\underline{dB}) \alpha F^{1/2}$. Rain attenuation in <u>dB</u> (not a technology factor but included for completeness) is approximately proportional to F^2 for a given scenario. The frequency dependence of technology is summarized in Table 2.2.

In summary, the laws of physics dictate that the performance of active devices and passive components decrease with increasing frequency. Consider a MILSATCOM system operating at EHF with the following assumptions: satellite antenna aperture is beamwidth limited due to coverage requirements, and terminal antenna is aperture limited due to vehicle compatibility. Then the <u>unstressed</u> performance would degrade at least 4.5 dB on an uplink using 45 vs

30 GHz and 7.5 dB on a downlink using 40 vs 20 GHz. These are lower bounds based only on consideration of mixer front end and power amplifier technology. Rain attenuation will be a factor of 2 and 4 higher in dB for 45 vs 30 GHz and 40 vs 20 GHz, respectively. Nevertheless, there may be system considerations that favor the selection of the higher frequencies.

C. Implementation Factors

The frequency dependence of technology discussed in the previous section ignored the associated implementation factors. With increasing frequency, the tighter tolerances make fabrication more difficult and yields lower. Increasing losses in active devices reduce gain and efficiency, in addition to output power. For TWT amplifiers, achieving a given level of output power with increasing frequency incurs higher operating voltages and more difficult beam-focusing and thermal designs. In the latter case, increasing frequency may dictate a change in cooling technique, i.e., from air to liquid cooling. For solid state devices the parasitic effects worsen with increasing frequency making the required circuit matching more difficult.

There are other implementation issues which are equally difficult to quantify but which must be addressed. For example, increasing the operating frequency of a terminal having a fixed antenna aperture may require the use of a more complex and costly tracking system, e.g., monopulse versus step tracking. Other implementation issues relate specifically to the frequency separation of the 45/20 GHz bands. At 30/20 GHz, a single feed providing adequate antenna efficiency and tracking performance is realizable based on the technology demonstrated at 6/4 GHz. At 45/20 GHz a dual feed requires development and demonstration of the requisite efficiency and tracking capability. The development of radomes for 45/20 GHz antennas is also required. The preceding paragraphs suggest the need at EHF for development in the areas of TWT and solid-state device fabrication technology, and of antenna systems with the emphasis on 45 GHz.

2.2 Industrial Base

This section assesses the industrial base at EHF from a "bottom-up" standpoint, i.e., first the availability of components and test equipment is

examined, next the production capability is assessed, and, finally the planned and potential EHF SATCOM interest outside the DoD is surveyed.

A. EHF Component and Test Equipment Availability

The millimeter wave band is traditionally defined as 30 to 300 GHz. However, past interest in the microwave spectrum extends to 40 GHz (the 26.5 to 40.0 GHz waveguide band was defined and components developed in the World War II era). Consequently, there are numerous microwave suppliers providing a complete line of waveguide hardware (bends, twists, hybrids, etc.) and laboratory components (attenuators, phase shifters, rotary joints, etc.) up to 40 GHz. Above 40 GHz, there are three major millimeter wave suppliers (Hughes, Alpha/TRG and Baytron) who essentially support all millimeter wave hardware and laboratory component requirements. (Hughes offers active devices and test equipment as well; Alpha/TRG also offers active devices.) Currently, a complete line of the necessary hardware and components is not available at 45 GHz. Consequently, those involved in technology development at 45 GHz must undertake the development of these components either in-house or under contract, either process being costly and time consuming. This added cost and delay could be incurred by each laboratory and system contractor, and the lack of component availability must be addressed. As an example of the experience at Lincoln Laboratory in this regard, rotary joints and source antennas required for testing prototypical 45 GHz antennas, must themselves be developed. When the components suppliers are solicited to undertake these developments, they unanimously respond that they do not have the necessary test equipment, must procure it, and must defray the cost in the component development. The availability of test equipment is appropriately the next topic.

Up to 18 GHz, the current status of test equipment technology is impressive and is typically all solid-state and computer compatible. The basic test equipment available includes sweep generators, frequency counters, spectrum analyzers and network analyzers. Such state-of-the-art equipment is available from numerous suppliers and encompasses automated test equipment (ATE). The microwave industry currently relies heavily on ATE to expedite

development and production testing, and to mitigate the need for technical personnel.

Above 18 GHz, test equipment capability can be extended in frequency by external peripherals, e.g., an additional EHF source is used as a local oscillator with an external mixer to downconvert the test signal to the frequency range of currently available equipment. However, this frequency extension process has several drawbacks: 1. the inherent performance of the basic test equipment is degraded by the peripherals; 2. engineering effort must be expended to assemble and debug the peripherals as compared with the simple purchase of a turnkey system; 3. the degree of automation possible is dependent on the availability of computer-compatible peripherals. The availability of test equipment above 18 GHz is improving, with all basic equipment operating directly up to 26 GHz, and most up to 40 GHz. Above 40 GHz, the only direct equipment available is the sweep generator (Hughes and Hewlett Packard). The current availability of EHF test equipment is summarized in Fig. 2.1.

The major test equipment manufacturer ($800 M/year), Hewlett-Packard (HP), provides a complete line of solid-state, computer-compatible instruments up to 18 GHz, including ATE systems for production testing. Most instruments are extendable to 40 GHz with external peripherals. HP is developing FET frequency multipliers and APC coaxial connectors to extend their equipment capability to 26 GHz in the near term, and to 40 GHz in the far term. They have no plans to extend their capability above 40 GHz.

The unavailability of complete test equipment is a problem which is common to numerous DoD programs operating in various portions of the millimeter (mm) wave spectrum, and which is currently receiving considerable attention. The future development, production and deployment of military systems at mm waves requires the development of such equipment capability. At EHF, the technology base is extant, and equipment development should be stimulated.

B. EHF Production Base

To support the deployment of EHF MILSATCOM systems, the necessary production capability is required. The production capability in the U.S. for

10-1405-N

NOTES:

- $*$ NO PLANS TO INCREASE FREQUENCY RANGE
- $\boxed{N}$ NUMBER INSIDE BOX DESIGNATES FREQ. LIMIT (GHz)

DESIGNATES:

- C SEE COMMENT
- x INDICATES EXTERNAL PERIPHERAL

ALL INSTRUMENTS BUS COMP EXCEPT WHERE INDICATED

	NETWORK ANALYZERS	SPECTRUM ANALYZERS	FREQUENCY SYNTHESIZERS	SWEEP GENERATORS	FREQUENCY COUNTERS	POWER METERS	COMMENTS
E-H INTERNATIONAL (Eldorado Instruments)					$\boxed{40}^{*}_{x}$		
EIP					$\boxed{40}^{x}_{C}$		DEVELOPMENT PLANS TO 100GHz
HEWLETT PACKARD	$\boxed{40}^{*}_{x}$	$\boxed{40}^{*}_{x}$	$\boxed{18}^{*}$	$\boxed{50}^{*}_{C}$	$\boxed{40}^{*}_{x}$	$\boxed{40}^{*}_{C_1}$	C-BUS COMP TO 22 GHz C-BWO TO 50 GHz C_1-BUS COMP TO 18 GHz
HUGHES				$\boxed{110}$		$\boxed{90}_{C}$	POWER METER HEADS ONLY
POLARAD		$\boxed{40}^{*}_{x}$		$\boxed{21}^{*}$			
SYSTRON DONNER			$\boxed{26}$		$\boxed{26}$		DEVELOPMENT PLANS TO 40 GHz
TEKTRONIX		$\boxed{60}$					PROVIDES MIXERS TO 60 GHz OPERATES TO 220 GHz
WATKINS JOHNSON			$\boxed{40}^{*}$				
WEINSCHEL				$\boxed{40}^{*}$			
WILTRON	$\boxed{40}^{*}$			$\boxed{40}^{*}$			

Fig. 2.1. Instrument survey: availability at 18 GHz and above.

microwave systems is currently limited to 18 GHz. A brief survey of major equipment manufacturers shows that there are no milimeter wave systems in mass production - a problem to be addressed in numerous DoD programs in this band. Production technology development is obviously required, but, how is it to be effectively implemented, who will support the necessary capital equipment investments, and how can industry be stimulated to respond? The promise that, "the mm-wave market is here", has been heard by industry for 25 years. Some manufacturers are quick to point out that the large mm market that was seemingly assured with the planned use of mm-waveguide transmission lines for telephone trunking was quickly supplanted by fiber-optic cable. In an analogous manner, the advanced detection, tracking and guidance systems that reach the production stage employ optical or infrared technology. The DoD must coordinate, plan and clearly state to industry its long range mm-wave requirements to elicit the necessary industrial support.

C. Non-DoD EHF SATCOM Interest

Interest in EHF SATCOMs outside the DoD will obviously provide additional support for the development of both technology and the industrial base. The most notable program in this regard is the NASA/LRC 30/20 GHz SATCOM program. The purpose of this program is to underwrite the development and demonstration of advanced SATCOM technology for future exploitation by the commercial carriers. The Phase I of this program addressed market-demand and system concept studies, and was completed in June 1979. The Phase II satellite technology developments are on-going, and are summarized in Table 2.3. A terminal development phase is to follow, and the program will conclude with a complete system demonstration in 1985. The market demand studies showed a saturation of both C-Band (6/4 GHz) and Ku-Band (14/11 GHz) in the 1990-1995 time frame, and projected a subsequent exploitation of the 30/20 GHz band. However, in the author's opinion, this projected time frame is quite optimistic. In particular, the implementation of frequency reuse techniques (e.g., antenna pattern and polarization isolation at C-Band and Ku-Band), which was not considered in the study, would greatly extend the available capacity, and the utility of the large capital investment in those

TABLE 2.3

NASA 30/20 GHz SATELLITE TECHNOLOGY DEVELOPMENTS

SUBSYSTEM	TECHNOLOGY DEVELOPMENT
30 GHz Low-Noise Receiver	FET Pre-Amplifier (NF = 5 dB) Parametric Pre-Amplifier
20 GHz Solid-State Amplifier	Linear 6-W FET Saturated 20-W IMPATT
20 GHz TWT Amplifier	Multi-Level 7.5 to 75 W (Saturated)
30/20 GHz Multibeam Antenna	Fixed and Scanning Beams Low Sidelobe Levels
Baseband Processor	Broadband (2.5 GHz) IF Switch Matrix Multiplexers and Modems

bands. In addition, the impact of competing technology, e.g., fiber optic cable, may deter the use of 30/20 GHz, particularly for high availability communications requirements. The level and time frame for commercial development of 30/20 GHz is difficult to quantify; the concomitant impact on the industrial base is obviously tenuous.

The most notable foreign interest in 30/20 GHz SATCOMS is in Japan. The Communications Satellite Experiment (CS-I) was launched in December 1977 and has provided valuable propagation data and operational experience. The contract for CS-II was awarded to Ford Aerospace and Communications Corporation (FACC) in October 1979. CS-II will provide Japan with the first operational 30/20 GHz SATCOM system in the world. The Italian Government recently approved a 5-year plan to develop and deploy a 30/20 GHz intracity trunking network. In the area of subsystems, satellite TWTs operating at 20 GHz have been developed in both Germany (AEG-Telefunken) and France (Thomson-CSF), and a ground terminal TWT operating at 30 GHz has been developed in Germany (Siemens), all under government sponsorship. These foreign technology developments will indirectly add to the domestic technology base through the exchange of scientific information. However, these developments will only impact EHF MILSATCOM deployment, if foreign suppliers are used directly.

Note that there is no non-DoD interest in 45/40 GHz SATCOMs either domestic or foreign. Consequently, SATCOM development in either of these bands must be totally funded by the DoD.

2.3 Summary

Selection of the 45 or 40 GHz bands versus 30 or 20 GHz must be made with an awareness of the imposed limits and lower performance of the technology, and the attendant implementation factors. Based on current technology, development of MILSATCOM systems operating in these higher bands will be more "difficult", take "longer" and cost "more". (It was beyond the scope of this report to quantify these factors; and it is doubtful that further studies will.) These factors do not imply that operation in these higher bands is not feasible. Rather, for those user communities whose unique operational

requirements force them to exploit these higher bands, this is meant to indicate that a more emphatic development effort is required and must be undertaken now.

There is a lack of component, device, subsystem and test equipment suppliers at EHF, particularly at 45 GHz. The most critical deficiency is the lack of the necessary test equipment. The need for such equipment extends from the developmental laboratories, to the hundreds of diverse component suppliers, to the production facilities, and finally to the DoD maintenance depots. These deficiencies are not unique to EHF MILSATCOM systems, but are shared by all DoD programs in the mm-wave band. In addition, there is no production capability within US industry at mm-wave frequencies, and extensive production technology development is needed - also a problem which permeates all DoD programs in this band. Industry is reluctant to undertake the necessary capital investment, having had the mm-wave "carrot" waved in front of them in the past. The burden is on the DoD to coordinate, focus and clearly state to industry its long range requirements and plans. The DoD must encourage the component, test equipment and system manufacturers to use their internal research and development (IR&D) allowances to advance the industrial base at EHF. The DoD, as a partner in this commitment to EHF, must maintain a steady, adequate level of support in these areas.

Finally, the development efforts of non-DoD agencies will contribute to the technology base at EHF, and should be closely monitored, supported, and jointly funded in overlapping areas. Commercial interest in the EHF bands is not expected to contribute to the domestic industrial base, certainly not in the near term.

III. TRAVELING WAVE TUBE AMPLIFIERS

3.1 Background

This section addresses traveling wave tube amplifiers (TWTAs) for application in EHF MILSATCOMs. As was discussed in Section I, studies have indicated that, based on current technology, the TWTA for the ground segment will represent a major cost factor in EHF terminals. It was further pointed out that the producibility and reliability of TWTs for the space segment continue to be a concern. Consequently, this section, in addition to assessing the capability of basic TWT technology, addresses TWT producibility, reliability and cost.

A. Assessment Methodology

The following methodology is employed for the assessment of traveling wave tube (TWT) amplifiers for both the ground and space segments. First the basic tube characteristics (power, frequency, and focusing and cooling techniques) are assessed vis-à-vis the capabilities of current technology. From this, the concomitant technological limits are defined. Next, the results from an in-depth survey of current tube manufacturers are reported, and their current capabilities are delineated. Wherever possible, data on operational experience is included. The assessment results are then summarized and, finally, recommendations are made for potential strategies to realize the requisite TWT amplifiers with minimum risk and cost.

The remainder of Section 3.1 presents a description of TWT fundamentals which provides a basis for later discussions of producibility and cost. Section 3.2 addresses TWTs for the ground segment and begins with a survey of the entire microwave tube market and of the commercial availability of TWTs. The material in this section is intended to place the EHF TWT "market" in the proper perspective. Section 3.2 then addresses: the technological limits and projected EHF TWT capabilities; the issues of producibility and cost; an in-depth survey of TWT manufacturers and current TWT availability, including data on operational experience; and, finally, recommendations for EHF TWT developments.

Section 3.3 follows the same methodology in assessing TWTs for the space segment. The issues of producibility and reliability of satellite TWTs is addressed vis-à-vis the current military (X-Band) and commercial (C-Band) experience. As discussed in Section I, 60 GHz TWTs for crosslink application are included as an obvious extension of EHF technology, and as a necessary adjunct to future MILSATCOMs.

B. TWT Fundamentals

The traveling wave tube is a thermionic, radio-frequency (RF) amplifier. The amplification is accomplished by interaction of an RF signal with an electron beam and subsequent transfer of energy from the electron beam to the RF wave. A simplified schematic of a traveling wave tube is shown in Fig. 3.1. The cathode or electron emitter, when heated, provides the source of electrons. A focus electrode to form the electron beam, and an anode to provide the accelerating field for the electrons are included with the cathode to form the commonly-referred-to electron-gun assembly. As the RF wave normally travels at the velocity of light and as it is not practical to accelerate the electron beam to a comparable velocity, a slow-wave circuit is required to delay the axial velocity of the RF wave in synchronism with the electron beam for efficient energy transfer. The electron beam, after traversing this interaction region, is dissipated in the collector in the form of heat. Since there is a natural repulsive force between electrons, a magnetic field is required along the slow-wave circuit to maintain the narrow electron beam. Permanent magnets are usually used for this function. Note the slow-wave circuit in Fig. 3.1 is a schematic representation of a helix, the most commonly used circuit. The diameter of the helix is typically in the range of 1/10 to 1/30 of a wavelength. As the number of helical turns per wavelength is dictated by the required axial velocity of the RF wave, the helix wire diameter scales in proportion to the wavelength. Consequently, the power handling capability of the helix circuit is ultimately limited by the wire diameter as the frequency increases. For high power, high frequency requirements, the coupled-cavity slow-wave circuit must be used. The coupled-cavity circuit consists of waveguide resonators that are coupled together by

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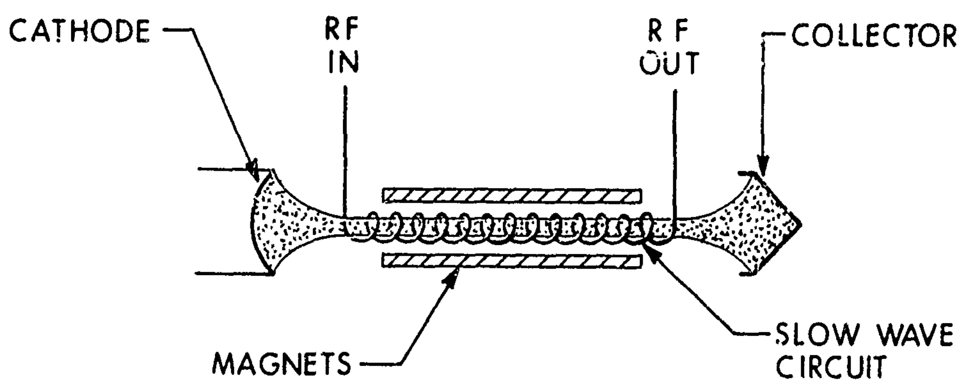

Fig. 3.1. Traveling wave tube schematic diagram.

means of inductive or capacitive apertures. Fig. 3.2 shows a coupled cavity part. Note the "ferrule" or raised hub surrounding the electron beam hole, it is designed to improve the interaction efficiency, and it requires the most critical tolerances in a coupled-cavity. Fig. 3.3 shows a section of coupled-cavity slow-wave circuit formed by stacking and brazing the cavity parts.

3.2 Ground Segment

A. Microwave Tube Market and Commercial Availability

The annual volume of the U.S. microwave systems market is approximately 1/2 billion dollars. The largest single expenditure item in a microwave system is usually the radio-frequency (RF) power amplifier tube. The total dollar volume of all microwave tubes for 1977 amounted to \$185M; CW TWTs accounted for 30%, \$55M, of this total[6]. A breakdown of dollar volume by tube types is shown in Fig. 3.4. The unit volume for the same year was less than 170,000 units; CW TWTs accounted for 15% of this, 24,700 units (Fig. 3.5). Comparing the bar charts of Figs. 3.4 and 3.5, it is evident that TWTs are low-volume and high-cost items in contrast to other tube types, for example, klystrons. The cost-per-unit ratio of TWTs is eleven times higher than that of reflex klystrons, \$2227/unit versus \$196/unit. The pulsed TWTs show the highest cost-per-unit ratio, almost four times that of CW TWTs, which reflects their inherent complexity. The cost-per-unit ratios of microwave tube types are shown in Fig. 3.6.

There are ≈34 manufacturers in the Free-World who are current, commercial producers of microwave tubes of all kinds (Fig. 3.7): backward wave oscillators, (BWOs), crossed-field amplifiers, (CFAs), klystrons (reflex, amplifier and oscillator), magnetrons, noise sources, duplexers (TR and ATR) and TWTs[7,8]. One-half of this number manufactures TWTs. Further restricting the categories to those who have TWT experience above 20 GHz, only eleven potential suppliers are available. These manufacturers, listed in Table 3.1, are known to have some experience in EHF TWTs, and form the basis for the TWT assessment for both the ground and space segments.

The availability of commercial TWTs by common frequency bands is shown in Fig. 3.8. Eighty-five percent of the total 1768 types are at 12 GHz or lower

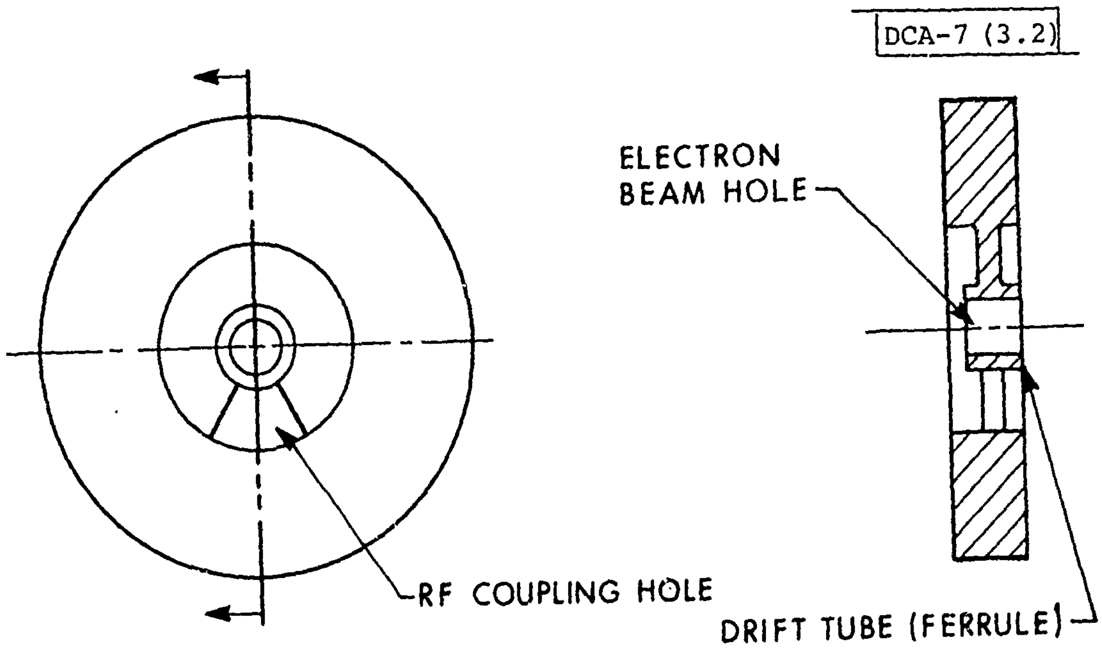

Fig. 3.2. TWT coupled-cavity part.

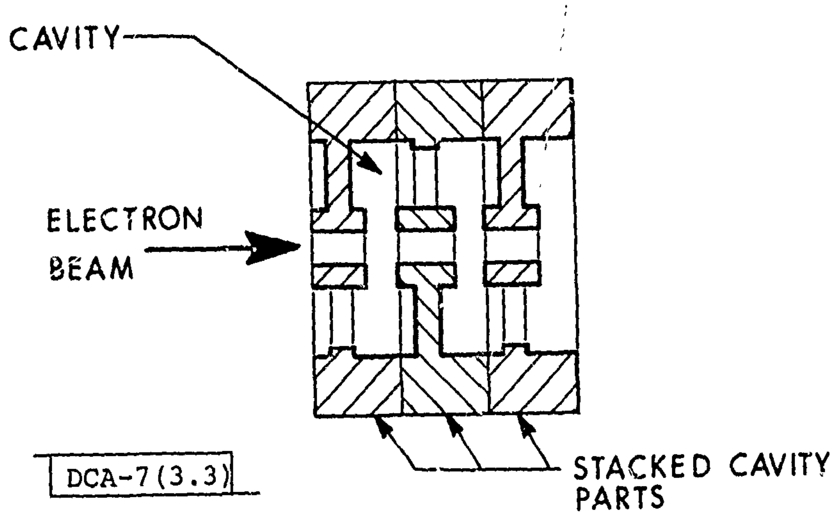

Fig. 3.3. TWT coupled-cavity slow-wave circuit.

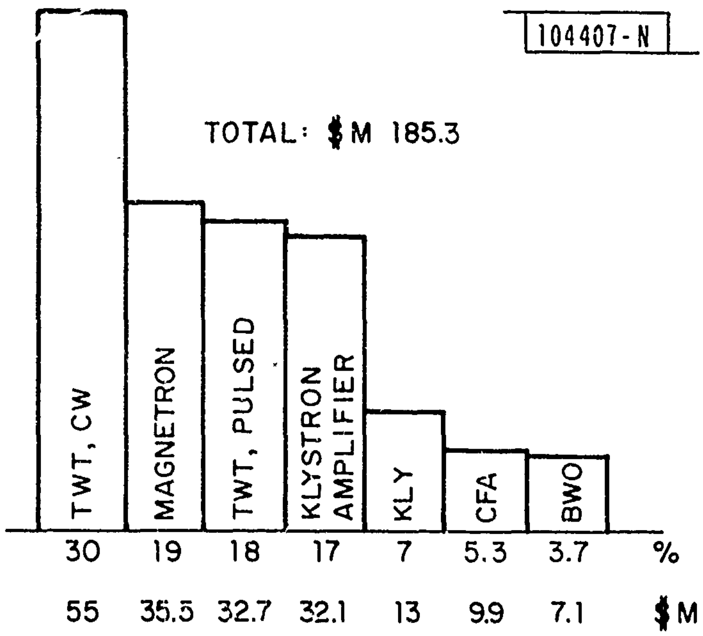

Fig. 3.4. Annual dollar volume of microwave tubes by tube type (After K. Garoff, Reference 6).

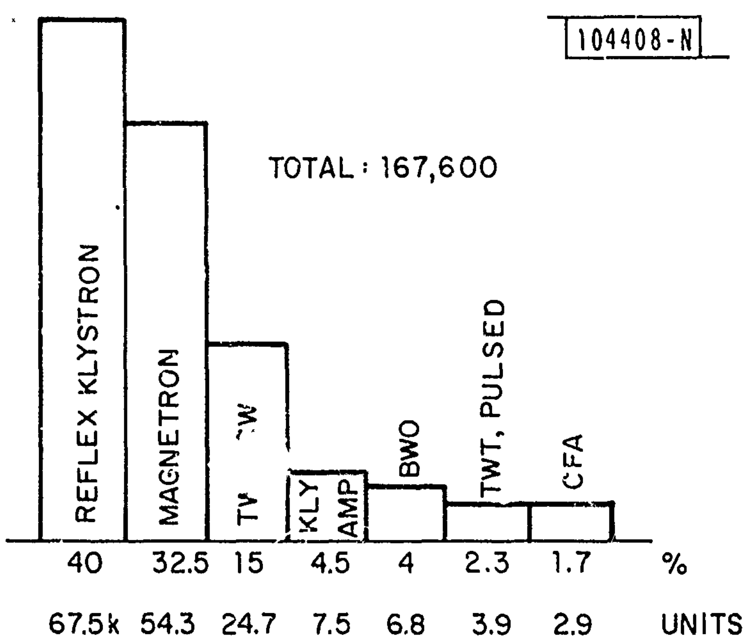

Fig. 3.5. Annual unit volume of microwave tubes by tube type (After K. Garoff, Reference 6).

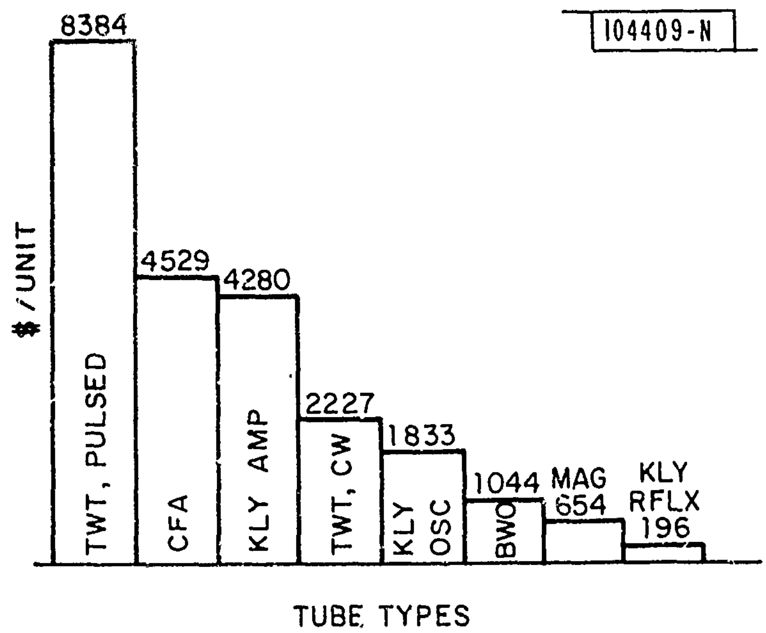

Fig. 3.6. Cost-per-unit ratios of microwave tubes.

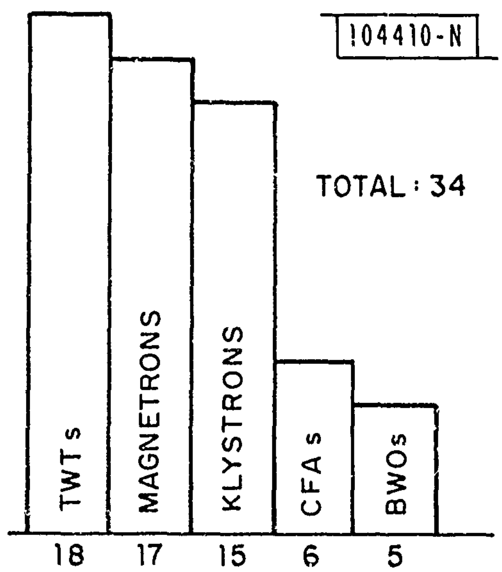

Fig. 3.7. Free-world microwave tube manufacturers by tube type.

TABLE 3.1

FREE WORLD MANUFACTURERS OF EHF TWTs

Japan	Nippon Electric Toshiba
West Germany	AEG-Telefunken Siemens
France	Thomson-CSF
USA	Hughes Aircraft Litton Raytheon Teledyne MEC Varian Watkins-Johnson

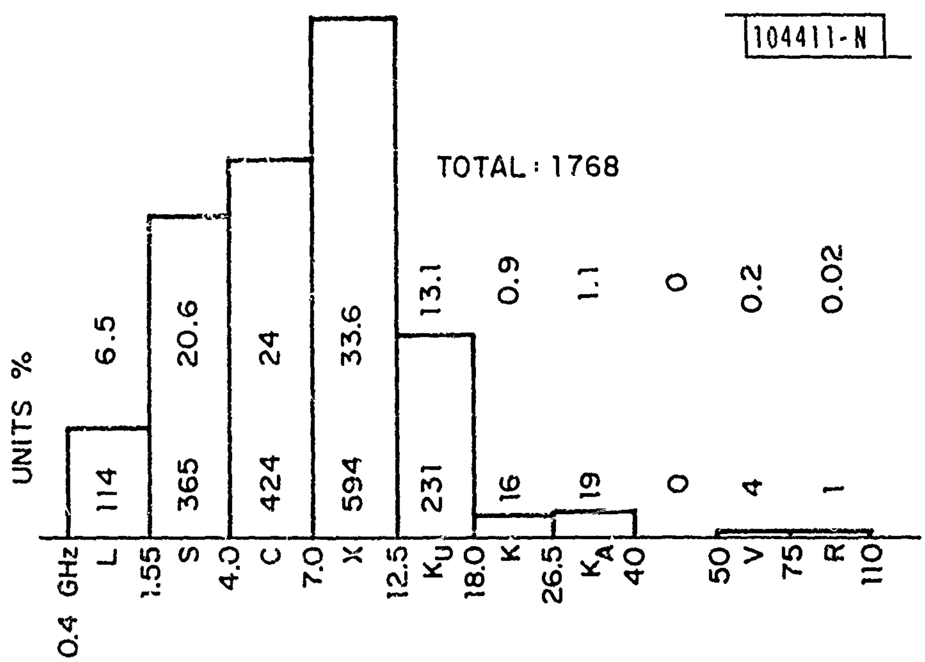

Fig. 3.8. Commercial availability of TWT amplifiers by center frequency.

frequencies; only 2 percent, or a total of 40 types, are above 18 GHz. There are no commercial tube types in the Free-World in the 40-50 GHz frequency band.

The commercial TWT amplifier types are listed in Table 3.2 and plotted in Fig. 3.9 by frequency bands assigned to present and future, civilian and military, satellite communications uplinks. The current commercial microwave relay (both satellite and terrestrial) category boasts of an impressively abundant selection: more than one hundred tube types specifically designed for the 5.9-6.4 GHz satellite uplink band are at the disposition of the terminal designer; the total number of TWT types that are capable of output over this range is three times that many. The tabulation includes only TWTs; klystrons, which could and do serve as RF amplifiers at these frequencies, are not included. The useful output power range is profusely covered with tubes delivering from 1.5 to 14,000 watts, and amplifier gains ranging from 30 dB to 60 dB. The amplifiers can be plugged into any practical source of power, direct current or alternating current of 50, 60, 400 Hz. The impact of a vigorous commercial market in this frequency band is evident.

Examining the TWT availability in the current military satellite band of 7.9 to 8.4 GHz, there is an abundance of tube types, albeit the selection is reduced by a factor of two. The designer of a current military satellite uplink apparently has half as many tube types to choose from as his commercial counterpart. The available output power levels and gains offer ample choices.

In the 14-14.5 GHz frequency band of future civilian satellite comunications, the activity is about 80% of all present military satellite communication activity. There are also just about as many power levels, gains, and input power requirements in this developing commercial band as there are in the present present military SATCOM bands.

It is not clear what level of commercial and military exploitation will occur in the uplink frequency assignments above 14 GHz. The available TWT amplifiers reflect this uncertainty quite clearly. There are only four commercial TWT amplifier types specifically for the 27.5 to 31 GHz band. This

TABLE 3.2

COMMERCIAL AVAILABILITY OF TWT AMPLIFIERS FOR SATCOM FREQUENCY BANDS

Frequency Band (GHz)	5.925 -6.425	7.900 -8.400	14.0 -14.5	27.5 -31	43 - 48
Application	Commercial Microwave Relay	Military Satellite Comm.	Future Civilian Sat. Comm.	Future Civilian/Military SATCOM?	Future Military Satellite Comm?
Total Number of Tube Types[1]	390	270	210	13	N/A[3]
Subset of Total[2]	108	49	39	4	0-(5)[4]
Ranges of Parameters of Subset					
Output Power	1.5W - 14KW	10W - 8KW	1/2W - 5KW	2, 3, 300W	100, 250, 500W
Cathode voltage,dc	1.2KV - 24KV	3KV - 19.5KV	2KV - 20KV	3KV - 17KV	14.5KV - 22KV
Cathode current	15mA - 3.8A	20mA - 3A	16mA - 1.8A	7mA - 260mA	46mA - 88mA
Gain	27dB - 60dB	27dB - 54dB	29dB - 60dB	27dB - 43dB	43dB - 50dB
Noise Figure	22dB - 42dB	24dB - 50dB	25dB - 38dB	---	----
Input Power					
frequency	dc,50,60,400Hz	dc,50,60,400Hz	dc,50,60,400Hz	AC, DC	DC
voltage	21,32,115,120, 208,230	110,115,208, 230	115,120,230		
Output Configuration	Waveguide,coax	W/G, coax	W/G, coax	W/G only	W/G only

[1]Any commercial TWT amplifier with output power over a frequency range that includes frequency band shown.

[2]A commercial continuous-wave TWT amplifier with at least half-watt output power over the given frequency range suitable for RF amplifier for ground terminal.

[3]No commercial types except QKW1993, .001 duty cycle, 500W, 46-56 GHz

[4]For lack of commercial types, in this column only, we include what exists: five development types 913H, 915H, 943H, 944H, V784

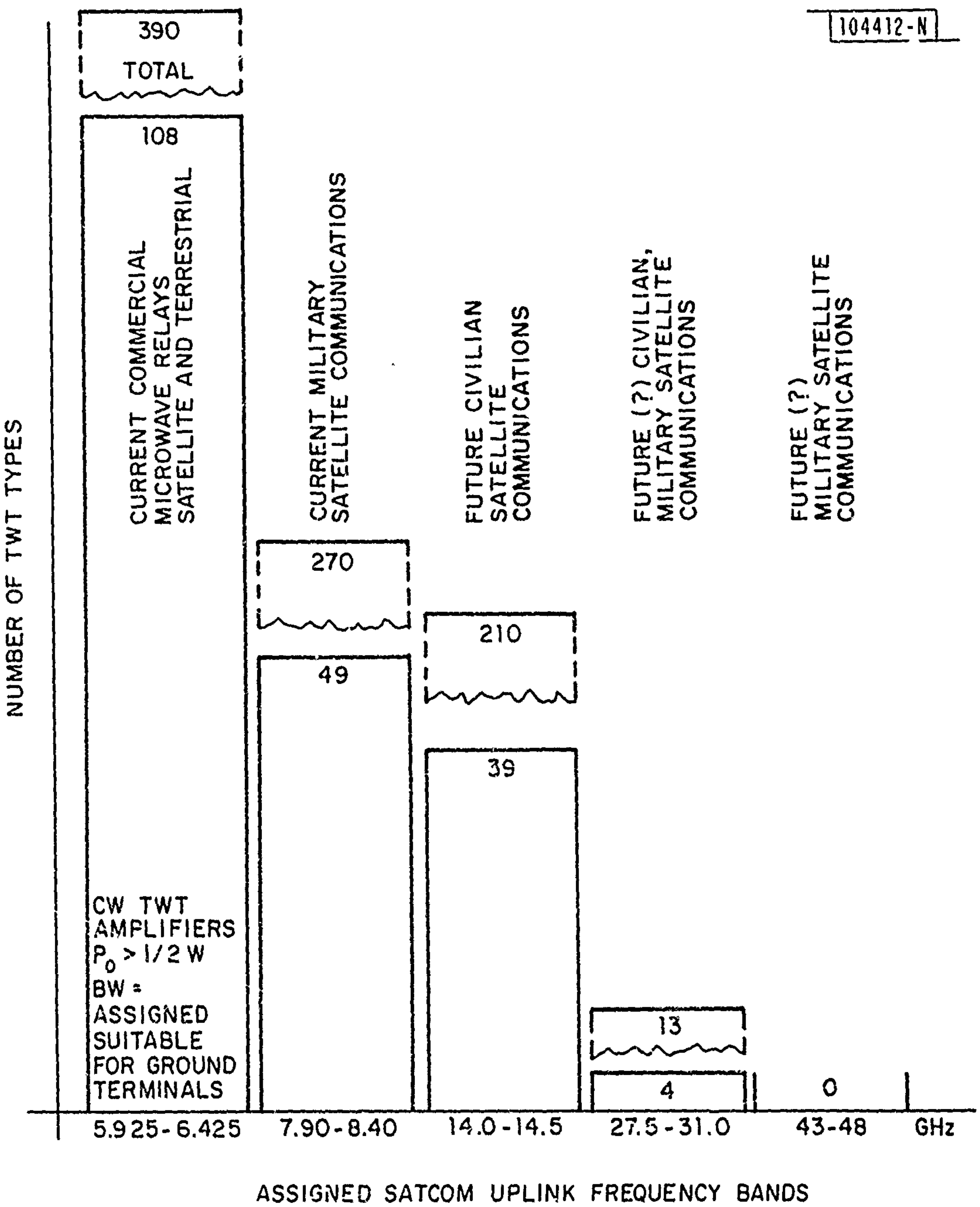

Fig. 3.9. Commercial availability of ground-terminal TWTAs by uplink frequency bands.

is a mere four percent of the TWT market for the present satellite communication band at C-Band. There are no commercial TWT types in the Free-World in the satellite communication band between 43 and 48 GHz.

B. TWT Characteristics and Technological Limits

Although klystrons are capable of providing adequate power for terminal applications, they are limited in bandwidth to a few hundred MHz as compared to a multi-GHz bandwidth capability for the TWT. The combined frequency and power requirements (> 100 W) for proposed terminals necessitate the use of a coupled-cavity slow-wave structure for the TWT as discussed in the previous section. The remaining tube characteristics to be defined are the focusing and cooling techniques employed and are also functions of both the frequency and power requirements. In addition, the focusing and cooling techniques are dictated by the operational constraints of the specific terminal, and hence, impose a limit on the available transmitter power. For beam focusing, the periodic permanent magnet (PPM) is preferred, particularly in mobile applications. A solenoid (electromagnet), in addition to being larger and heavier, typically requires prime power which equals or exceeds the beam power of the tube. As the solenoid power is dissipated in ohmic loss, the cooling requirement for the TWTA is increased accordingly. Liquid cooling of the TWT may be undesirable for airborne and small ground-mobile terminals due to the additional space, weight and maintenance requirements. Fig. 3.10 presents projections of EHF TWT capability as a function of focusing and cooling technique. The projections are derived from technical articles and discussions, and are based on current technology, i.e., demonstrated technology amenable to "production" in < 3 years. (Note that far term projections based on state-of-the-art technology are also included in Fig. 3.10.) The differences in the predicted power levels and in the frequency dependence of the projections reflect the differences in the basic technology of the manufacturers. Table 3.3 summarizes the near-term projections for 30 and 45 GHz. Note that these estimates represent the current state of TWT technology at EHF. Consequently, proposed tube developments at higher power levels should be considered high-risk efforts.

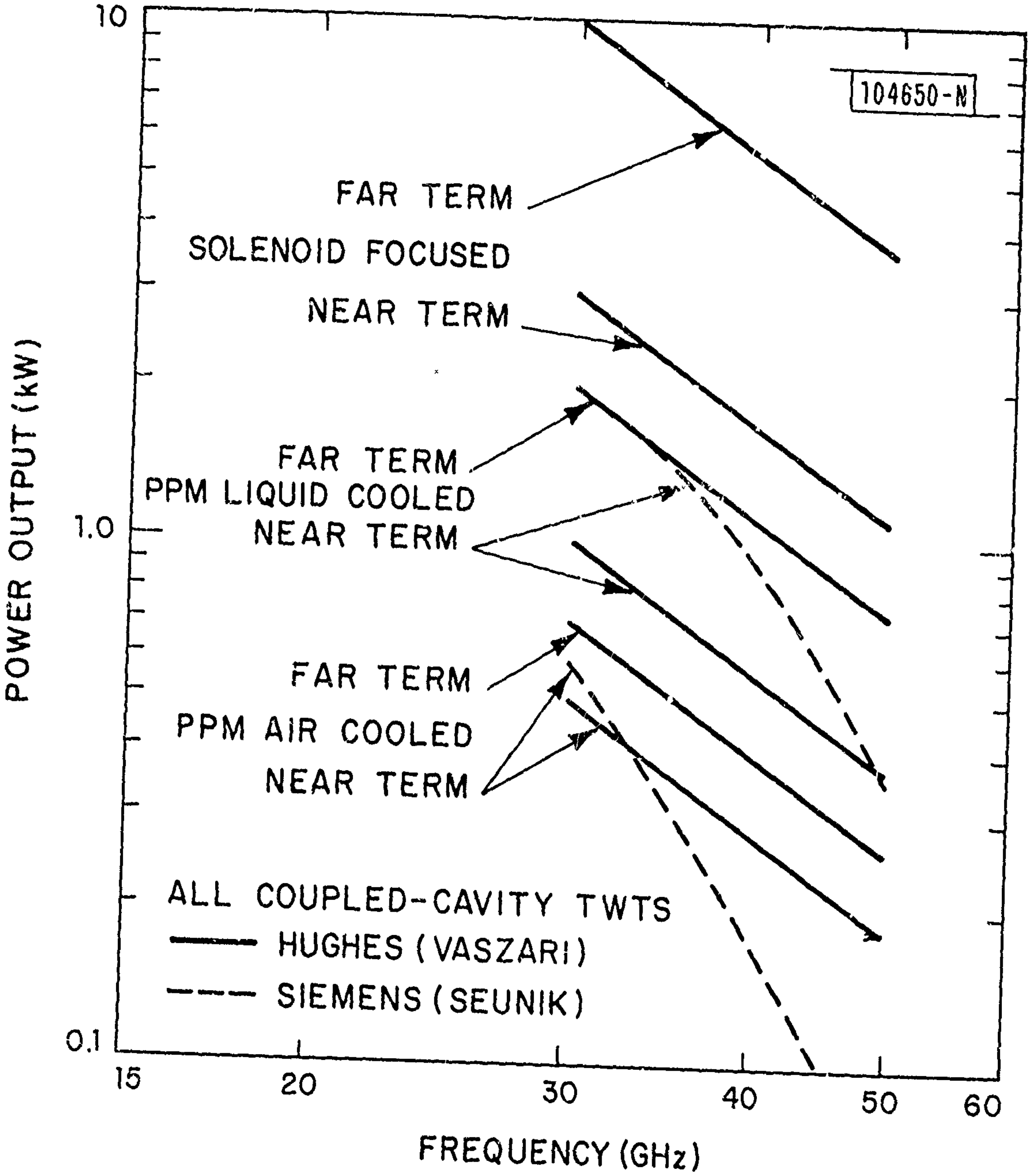

Fig. 3.10. Technological limits of EHF TWTs for the ground segment.

TABLE 3.3

EHF TWT NEAR TERM PROJECTIONS*: GROUND SEGMENT

TWT CHARACTERISTICS	POWER (WATTS)	
	30 GHz	45 GHz
AIR COOLED** (Airborne and Ground Mobile)	500	250
LIQUID COOLED** (Shipboard and Fixed)	1K	500
SOLENOID FOCUSED (Fixed Terminals)	2K (10K)***	1K (5K)***

*Manufacturers' estimates based on current coupled-cavity technology

**PPM Focused

***Far-term estimates based on laboratory demonstrations

C. TWT Producibility and Cost

Prior to presenting the results from the survey of TWT availability, it is appropriate to address the critical issues of producibility and cost. The required slow-wave circuit for a high-power TWT typically consists of 150 coupled-cavity parts which require fabrication and assembly to tolerances of the order of 50×10^{-6} inches. The cavity parts must be carefully screened (typically 50% yield), assembled in a test fixture for cold tests (RF bandpass characteristics), brazed to the same stringent tolerances, and finally assembled with the other TWT components. The assembly and cold testing are very labor intensive, as the marginal reproducibility of the parts may necessitate several iterations of the process. The tolerance requirements on the cavity parts are at the limit of current machining capability and few vendors are available. Consequently, the cost is $100 per cavity, and the delivery time is ≈ 9 months. The high cost of the basic cavity parts and of the required assembly make the coupled-cavity circuit the cost driver in EHF TWTs (current cost $\approx$ \$100K). Considering the large number of critical-tolerance parts and processes, the corresponding resource investment, and the present lack of a potential market, it is understandable that there are few potential suppliers. Even with the current suppliers, the task remains to transition EHF TWT technology from the current development stage to a production capability, with a concomitant decrease in cost and increase in reliability. The accomplishment of this transition requires production technology development programs. As the exploitation of EHF is primarily a DoD need, DoD funding is required to accomplish this necessary transition. (Note that there is currently some NASA and foreign interest in 30 GHz SATCOMS.) Several such DoD-funded production technology programs are already in progress and they are discussed next.

Possible approaches to improving EHF TWT cost and producibility include:

1. Fabrication of lower-cost, better tolerance cavity parts for existing tube designs.
2. Modification of existing cavity designs for reduced tolerance requirements and ease of fabrication.
3. Development of less complex slow-wave circuits.

These approaches are listed in order of increasing risk and development effort, and in order of increasing producibility and decreasing cost. Efforts are in progress in all three areas. Hughes is pursuing two programs related to their 915H TWT (250-watt, Q-band tube). One program, referred to as the "diamond turning" program (NOSC funded) is directed toward producing lower-cost, better-tolerance ferruled cavity parts for their existing tube design. Diamond turning is a precision machining technique with software-controlled machinery, air bearings, temperature controlled environment, and a single point diamond cutting tool. The anticipated tolerances using this technique are in the order of $\pm 15 \times 10^{-6}$ inches and the projected cost per cavity is in the order of $20 to $50. If the cavity parts meet the expected tolerances, the assembly and cold-test costs will also be significantly reduced. Recently, an experimental program was concluded which successfully demonstrated the feasibility of the diamond turning process. Follow-on work will be directed toward establishing a production capability for millimeter wave TWT cavity parts. Diamond-turned cavity parts will be available for use in 915H TWTs in mid-1982.

The other improved-producibility approach being addressed at Hughes is the "ferruleless" circuit program funded by RADC/OCTP. The RF cavity of the ferruleless design eliminates the raised hub portion (Fig. 3.2) and consists of two flat parts, a "washer-like" cavity part and flat web containing the electron-beam and RF-coupling holes. The main advantage of the ferruleless design is that the cavity parts are amenable to manufacturing by fine blanking (coining) techniques and double disk grinding. Estimates of production cost per cavity are in the order of $10 to $20. In addition, this design relaxes the tolerance requirements on the cavity by approximately a factor of two. Again, production of parts with a good reproducibility will result in a savings in assembly and cold-test labor. However, the ferruleless design has inherently lower efficiency and lower gain per cavity than a comparable ferruled design. In Phase I of this program, ferruleless cavity parts were fabricated by standard machining techniques. A tube was constructed using these parts and tested in December 1979. The tube failed at 5% duty cycle due to a filament failure. Prior to failure, the tube demonstrated 250 watts

output power indicating that the efficiency and gain are sufficiently high to produce the desired output power. However, the bandwidth was substantially less than other designs, and the intercavity coupling will have to be increased to meet the required bandwidth. Phase II of the program is currently in progress and consists of first developing the fine blanking manufacturing capability for ferruleless circuit parts. Performance data on the second tube, with the required broadband design modifications incorporated, is not expected until December 1981 at the present level of funding. RF performance comparable to the 915H remains to be demonstrated, as well as the capability of the coining technique to provide adequate tolerances for the cavity parts.

In the area of developing new slow-wave circuits, several programs are in progress. Most notable of these is the "folded waveguide" circuit development at Raytheon under AFAL sponsorship. (The folded waveguide circuit is literally a rectangular waveguide which is folded in a "serpentine" or "accordion" fashion.) The advantage of this tube design is its ease of producibility and concomitant potential for low cost. Consequently, the emphasis in the program to date has been directed toward fabrication technology. Specifically, several viable techniques have been examined for producing the electron-beam hole in a copper block. The required waveguide pattern is then machined in the copper block by the electric discharge machining (EDM) process (a moving wire electrode cuts the required pattern by electrical discharge under computer control). The addition of two cover plates to the copper block forms the rectangular waveguide circuit, and hence, the entire slow-wave structure is fabricated with only four parts. Estimates of cost in production quantities are of the order of $25K per tube. However, the potential advantages of mechanical simplicity and low manufacturing cost are somewhat offset by reduced interaction efficiency and lower gain than coupled-cavity circuits. The design objective is to achieve 500 watts of output power and 40 dB gain at 46 GHz. The current phase of the program will provide the first RF performance results and is scheduled for completion in June 1980.

Another attractive slow-wave circuit is under development by Litton (Electron Tube Division) under IR&D. The RF circuit is called a HIGHTRON (acronym for Helix In Guide Hybrid), and, like the coupled cavity, is a loaded-waveguide, traveling-wave circuit. However, the large number of cavities required for the latter are replaced by a single subassembly of helix and brazed support planes. The use of a helix in the slow wave structure leads to a high interaction impedance which allows the circuit to be larger than that used in coupled cavity tubes of the same frequency and power. The combination of all metal brazed construction and large cross section of the HIGHTRON is predicted to provide average power capability comparable to current coupled-cavity TWTs. (Current CW power output projections for the HIGHTRON include: 2 KW at 18 GHz, 1 KW at 35 GHz, and 400 W at 60 GHz, all with $\approx$ 10% bandwidth.) However, the cost of producing a HIGHTRON helix for EHF is estimated to be 1/3 to 1/5 the cost of a coupled-cavity TWT of comparable performance. Two HIGHTRON tubes have been fabricated and tested at $\approx$ 17 GHz. The first tube suffered from backward wave oscillations (BWO). The second tube was designed to eliminate BWO and demonstrated 5.6 KW of peak power with 28% efficiency and > 60 dB gain at 17 GHz (beam voltage = 25 KV). (The output coupler of this tube was inadvertently broken, and, consequently, the evaluation was not completed.) This tube displayed a periodicity in gain and output power which is attributed to the coaxial coupling used on the input and output circuits. Alternative methods of exciting the HIGHTRON circuit are being investigated and need to be demonstrated.

Several slow-wave circuits are under development at Varian. Most notable of these is the "Comb-Quad" circuit (four "comb-like" metal structures which are aligned orthogonal to each other along the tube axis to form the slow-wave circuit) which is being developed under Air Force (RADC) and Navy funding. Each comb may be cut from a single strip of copper, thus eliminating the errors in and cost of stacked cavity parts. The concept would also provide a mechanically rugged circuit at EHF. Although extensive analysis and cold tests (measurements of dispersion curves and interaction impedance) have been conducted, no Comb-Quad tubes have been developed for hot tests. Another

slow-wave circuit under development at Varian under NASA sponsorship is the "TUNNELADDER" circuit. It is being developed to provide several hundred watts of power in the 40 to 50 GHz band for possible space application. However, the current design has relatively narrow bandwidth, i.e., 1%.

D. Survey of TWT Manufacturers and Current Availability

Table 3.4 contains a list of the tube manufacturers surveyed as potential suppliers of EHF TWTs. Several of these manufacturers, e.g., Litton and Raytheon, are primarily suppliers of ECM tubes. Varian has several R&D programs in progress that are directed toward EHF TWTs, but is not currently producing or responding to requests for such tubes. Watkins-Johnson has not expressed any current interest in high-power EHF TWTs. Other manufacturers, e.g., Teledyne MEC (8 GHz), AEG-Telefunken (15 GHz) and Thomson-CSF (15 GHz) produce communications TWTs but at frequencies below 18 GHz. There are only two manufacturers that currently appear to have an appropriate EHF TWT capability: one domestic (Hughes) and one foreign (Siemens). Raytheon is included as having potential, rather than current, capability.

Table 3.5 contains results of the survey of TWT technology relevant to EHF terminal requirements. These results are believed to represent all the applicable high-power, EHF TWT technology in the free world. The tube developed by Toshiba for the ground terminals of the Communications Satellite (CS) system, while providing high power with air cooling, employs an electromagnet (solenoid) for focusing. This tube, which requires $\approx$ 2.7 Kw of prime power, with the solenoid requiring an additional 2.7 Kw, is not considered appropriate for MILSATCOM terminal applications. Also note that, with the additional exception of a 30 GHz tube being developed by Siemens for the German Ministry of Defense, all EHF TWT developments are funded by the DoD.

Table 3.6 summarizes the EHF TWT experience of Hughes and Siemens. The only air-cooled tubes developed (913H and 914H) have not been incorporated into a complete transmitter, are in bonded storage, and have no operating experience. The 913H tubes were developed for NOSC as backups to the Siemens tubes (V-684) for the LES-8/9 experiments (Clarinet Omen), but were not

TABLE 3.4

TWT MANUFACTURERS SURVEYED

Manufacturers Surveyed

Hughes Electron Dynamics Division

Litton Electron Tube Division

Raytheon Power Tube Division

Teledyne MEC

Varian Microwave Tube Division

Watkins-Johnson

AEG-Telefunken

Siemens

Thomson-CSF

Candidate EHF Terminal TWT Manufacturers

Hughes

Siemens

Raytheon (potential)

TABLE 3.5

CURRENT EHF TWT TECHNOLOGY: GROUND SEGMENT

COOLING	FREQ (GHz)	MFG/ MODEL	POWER (W)	EFF (%)	GAIN (dB)	BW (GHz)	COMMENTS*
Air	30	Hughes 914H	200	25	36	1.0	Developed for SATCOMA
	37.4	Hughes 913H	100	25	45	2.0	Developed for NOSC
	44	Hughes 915H	250	25	50	2.0	In Development NOSC
	44	Hughes 915HA	250	25	50	2.0	In Development RADC
	44	Siemens V-884	150	27	40	2.0	In Development AFAL AN/ASC-30
	30	Toshiba ---	400	16	41	1.0	CS Terminals Solenoid*
Liquid	30	Siemens ---	1200	25	43	2.0	Developed for German Govt
	37.4	Siemens V-684	1000	25	41	1.5	NOSC/NRL/AFAL LES 8/9 Tests
	44	Hughes** 915H	250	25	50	2.0	Developed for NOSC
	44	Siemens V-784	500	14	43	2.0	Developed for AFAL AN/ASC-28

*All tubes PPM focused unless otherwise indicated

**Originally proposed as air cooled

TABLE 3.6

EHF TWT EXPERIENCE: GROUND SEGMENT

MFG	MODEL	FREQ (GHz)	POWER (W)	NO. OF TUBES	TUBE RELIABILITY
Hughes	913H	37.4	100	2	In Storage (NOSC), No Data
	914H	30	200	2	In Storage (SATCOMA), No Data
	915H	44	250	5 (13)	1 Tube, 1000-HR Life Test
	915HA	44	250	1 (2)	No Data
Siemens	V-584	37.4	1000	9	3 (NOSC), Life < 400 HRS 4 (AFAL), Life > 1000 HRS
	V-784	44	500	1	In Storage (AFAL), No Data

utilized. Note that the 915H was originally proposed to the Navy (NOSC) to be air cooled, but liquid cooling was required due to noise considerations for submarine application. During Phase I and II of the 915H development program funded by NOSC, five (5) TWT assemblies were started and three (3) tubes were tested and delivered. Two (2) tubes encountered assembly problems in fabrication. S/N 2 and 3 exhibited 220 watts of power output over a wider bandwidth than required. These two tubes had a narrower margin of beam voltage stability than required and an instability existed (higher order mode). A 1000 hour life test was successfully conducted on S/N 2 with no sign of performance degradation. A design refinement was successfully accomplished which increased the beam voltage stability range and eliminated the higher mode oscillation. S/N 4 was built, tested, and delivered (power output $\approx$180 watts). S/N 4 was subsequently damaged during transmitter integration testing. Phase III and IV were recently funded to design, refine and build eight (8) additional 915H TWTs. The current design refinement will increase the power output to the required 250 watts. During this effort, four (4) 915H TWTs will be built with liquid cooling and four (4) TWTs will be air cooled. In addition, diamond turned cavity parts will be used in the manufacturing of the last four (4) tubes. (Hughes anticipates a follow-on diamond turning effort will be funded.)

The Siemens V-684 was developed for DoD experiments with the LES-8/9 satellites. The three tubes operated by NOSC each exhibited an operating life of 400 hours or less, and no tubes are currently operable. The AFAL experience with the V-684 has been more favorable, i.e., a total of 5000 hours of operation has been accumulated on their four tubes, and all tubes are still operable. (The remaining two V-684 tubes were operated by NRL in jammer-simulator experiments, and no operating data was obtained by the authors.) The Siemens V-784, operating at Q-band, is a scaled version of the V-684 (as opposed to an optimized design) as indicated by the low efficiency of 14% (see Table 3.5). This tube is in storage and has not been used operationally. Note that only ten (10) EHF tubes have been fabricated by each supplier. Note also that the reliability data on these tubes is indicative of the

developmental state of the technology. The need for production technology development programs is evident.

Raytheon has no current experience in producing EHF TWTs for MILSATCOM systems. However, they have potential capability in several areas. Raytheon has developed diamond-supported helix technology which improves the thermal and power handling capability of the helix structure over that of more conventional dielectric supports. They have proposed (to the Navy) the development of an 80-watt, Q-band TWT based on the diamond support rod technology. Even at this power level, the realization of such a tube remains to be demonstrated. The achievement of power levels appropriate for most proposed terminal requirements is believed to be unlikely even though studies (Raytheon, Hughes and Varian) have indicated a potential output power of 200 watts at EHF for a diamond-supported helix. More relevant to EHF terminal requirements is Raytheon's technology transfer program with Siemens (sponsored by AFML). This technology transfer includes: a licensing agreement for Raytheon to produce Siemens tubes; purchase of drawings, computer programs and design information; and an assembly and manufacturing phase by Raytheon with Siemens technical support. The objective is to establish a domestic manufacturer of EHF TWTs derived from the Siemens technology. The program includes the fabrication and assembly of four Siemens tubes (V-684) by Raytheon, and will be completed by the end of 1980. As Siemens does not currently have 30 or 45 GHz TWTs with the peformance required and Raytheon must experience a maturation phase, TWT availability will depend heavily on the levels of effort and funding at both companies. As described in the previous section, Raytheon has a current program under AFAL sponsorship to develop the folded-waveguide, slow-wave circuit. This technology remains to be demonstrated, but has the potential for rapid transition to a production phase.

E. Medium Power TWTs

To this point, the assessment has focused on TWT technology which is capable of providing output power in excess of 100 W, these power levels being typical of most proposed EHF MILSATCOM terminal requirements. However, there

may be applications requiring output power of the order of 25 to 50 W. This potential requirement would apply for single-channel, tactical terminals whose output power level was dictated by prime power limitations, cost constraints and/or compatible satellite designs (e.g., the Lincoln Laboratory EHF technology demonstration or "Current System" concept). The significance of operating at the 25-to-50 W level is that helix technology becomes a viable alternative with the cost of a helix tube estimated to be 1/3 to 1/5 the cost of a coupled-cavity tube. (Note that there are projections of 100-to-200 W helix tubes at EHF, but, in the author's opinion, if such tubes were developed they would not have the necessary high producibility and reliability at these high power levels.) Current helix TWT development programs include Raytheon efforts (IR&D) to develop a 20-W, CW TWT in the 20 to 40 GHz band. Results to date include the successful demonstration of a wire-wrapped, 3-point boron nitride-rod-supported helix which provides ≈ 5 W over this frequency band. Raytheon has developed (Navy sponsorship) helix TWTs at a slightly lower frequency band which employ the wire-wrapping technique and diamond support rods. Another helix TWT development program is being conducted by Varian under RADC/OCTP sponsorship. This tube program, originally intended for satellite downlink application (40-41 GHz), is a two-year program which began in June 1979. The contract requires delivery of only one tube (no power supply) but a price quotation was obtained for purchase of 12 subsequent tubes. The additional tubes would be used for shock and vibration, destructive, and life tests. The tube specifications are: 40-44 GHz* frequency range; 10 watts output power; 20% minimum efficiency (single depressed collector); 35 dB minimum gain (saturated); 70,000 hr. life; PPM focusing; Type M (impregnated) cathode; and 8 Kv beam voltage. RADC expects these objectives to be easily achieved. Note that, as the tube was initially designed for satellite application, tube reliability and life are being emphasized. It would be a cost-effective method for medium-power helix tubes

*As the helix is inherently a broadband circuit, optimizing tube performance for 43-45 GHz will require only modification of the input and output matching circuits.

for potential EHF ground terminal application to approach the development from high-reliability, space tube technology.

The development of a 25-W version of the 10-W tube is an RADC planned FY-81 program. It will be a 1 year program which parallels the 10-W tube development. The 25-W tube will use the same helix and collector as the 10-W tube, but will require a new gun and a single permanent magnet to improve beam focusing. RADC is confident about the technical feasibility of this development. Varian estimates that the cost of this tube in production quantities would be $15-20K.

F. Summary

Currently available, high-power (> 100 W), EHF TWTs employ coupled-cavity, slow-wave circuits. This technology (Table 3.3) is capable of supporting most proposed high power amplifier requirements. However, as noted in Section I, the salient technological issue is not what level of performance EHF technology can support, but rather, what level of EHF technology is producible, reliable and affordable. Examining this latter aspect of current TWT technology, note that the requisite tight tolerances and high number of cavity parts, combined with the intensive assembly and test labor, result in the TWT potentially being the major cost factor in EHF MILSATCOM terminals. There are currently two suppliers of EHF TWTs: one domestic (Hughes) and one foreign (Siemens). There have been only ≈ ten EHF TWTs built by each of the manufacturers. The level of operational experience, MILSPEC qualification and life testing is minimal. Consequently, current EHF TWT technology must be considered in the developmental stage. The cost of an EHF TWT at the present time is > $100K (HPA cost > $250K).

The producibility, cost and reliability issues must be addressed now to support an orderly, low-risk evolution to affordable EHF MILSATCOMs in the next decade. Development effort and support are required and are recommended in the following areas:

1. Improve the producibility and reliability of current coupled-cavity TWTs.
2. Develop and evaluate alternative slow-wave circuits.

3. Develop TWTs with requisite power output having user-terminal-compatible focusing, cooling and prime power requirements.

4. Perform MILSPEC qualification and life tests.

1. Coupled-cavity TWT technology is the most mature and has demonstrated the requisite performance capability. Development effort is required in the areas of cost reduction, and producibility improvement, and two such programs are in progress. The diamond-turning technique (Hughes/NOSC) is a "no-risk" approach to fabricating ferruled cavity parts to the needed tolerances. The potential reduction in the cost of the parts is known. It is necessary to fabricate a tube using these parts to estimate the cost reduction in the assembly and testing. The last four (4) 915H TWTs in the NOSC procurement would provide such an evaluation. The ferruleless circuit development (Hughes/RADC) offers the potential for further cost reduction. However, the RF performance of the ferruleless circuit will not be known until December 1981 at the current level of funding. It is recommended that these technology improvement programs be supported to bring current EHF TWT technology to its maximum producibility and minimum cost.

2. Alternative slow-wave circuits are in various phases of development and are projected to provide TWTs costing 1/3 to 1/5 the cost of current coupled-cavity tubes. Most notable among these developments are: the HIGHTRON (helix brazed to two support planes), a Litton development (IR&D) which has demonstrated 5.6 KW at 17 GHz; the folded waveguide (serpentine waveguide structure), a Raytheon development (AFAL funded) which is scheduled for demonstration in mid-1980; the Comb-Quad (four orthogonal comb structures), a Varian development (currently RADC and Navy funded) which has been analyzed and cold tested, but not demonstrated. All of these development efforts have several factors in common: capability of high output power at EHF, simpler slow-wave circuits with few parts, and amenability to low-cost production; but also, a lack of demonstrated RF performance, and low-level funding with concomitant long development schedules. It is recommended to expedite the development and evaluation of these alternative circuits to allow the judicious selection of the technology appropriate for EHF MILSATCOM terminal deployment.

3. TWTs with user-unique operating characteristics require development, but should await the choice of a circuit technology with the demonstrated producibility as well as performance.

4. The final recommendations address the implementation of test and evaluation programs. The test program would consist primarily of MILSPEC qualification and life tests, to be followed by terminal integration and operational evaluation. Note that it is necessary to procure multiple TWTs to conduct such tests in a timely manner. Current delivery of an EHF TWT is $\approx$ one year, and a scheduled test program could not tolerate such delays to replace a failed tube. The scheduling of such a test and evaluation program should await the emergence of the appropriate technology.

In summary, the critical issue regarding EHF TWTs is the development and demonstration of producible, reliable and affordable tubes. Numerous tubes are in varying stages of development under the sponsorship of various agencies (and under IR&D funding). The levels of funding are too low and the concomitant development schedules too long. The various DoD agencies providing the funding are operating under budget constraints which dictate the current level of support. However, these tube developments will not cost less if protracted, and, more importantly, are a necessary first step to the development, qualification and deployment of EHF terminals. It is, therefore, recommended that to provide the substantial and sustained funding required, broad support be solicited within the DoD and NASA. This concerted effort would support and fund the development and demonstration of these potential technologies, and evaluation and selection of the appropriate technology.

3.3 Space Segment

This section assesses EHF TWT technology for the space segment and follows the same methodology employed for the ground segment tubes with one exception. The issue of TWT producibility and reliability for the space segment is addressed by assessing the past and current experience with SHF satellite TWTs, comparing it with commercial C-Band TWT experience, and, finally, by surveying on-going and proposed space TWT improvement programs.

As will be evident in the following sections, the technology base for EHF satellite TWTs is very limited. Consequently, the assessment relies heavily on projections, study results, planned developments, and prototypes.

A. TWT Producibility and Reliability

The TWT manufacturers listed in Table 3.4 were surveyed to determine suppliers of SHF, space qualified TWTs. Although the majority of the manufacturers listed have TWT capability at SHF, imposing the requirements of space qualification results in only four candidate suppliers: two domestic (Hughes and Watkins-Johnson) and two foreign (AEG-Telefunken and Thomson-CSF).

Table 3.7 contains the results of a survey of SHF TWT technology relevant to MILSAT application. Hughes supplied the 20-watt tubes for DSCS-II and NATO-III. Hughes and Watkins-Johnson are dual contractors for the 10- and 40-watt DSCS-III TWTs. Thomson has developed and space qualified a 20-watt, 8.2 GHz TWT for a commercial Earth Observation Satellite being built by Matra for the French National Space Agency (CNES). Thomson has also developed, but not space qualified, a derivative of this tube operating at 7.3 GHz for a military application. The emphasis in space TWT development at AEG-Telefunken is on direct-broadcast satellite applications at 12 GHz, and Telefunken does not have current SHF TWT capability.

Thomson-CSF is developing C-band TWTs for the commercial market but has not yet space qualified them. The X-band tubes discussed previously have been developed and/or flight qualified, but not flown. The most significant Thomson space TWT effort has been the development, space qualification and delivery of seventy 10-watt, Ku-band (12 GHz) TWTs for the INTELSAT-V (I-V) satellite. They have conducted extensive life tests (55 tubes on life test) on this tube and report 1.7×10^6 hours without a failure, and 45,000 hours on a single tube. Their unique technology consists of a patented brazed copper helix design (i.e., copper helix brazed to beryllium oxide support rods which are themselves brazed to the stainless steel vacuum envelope), and impregnated (dispenser) cathodes. To summarize the experience of Thomson-CSF, they have no flight experience and, consequently, their potential capability is unproven. However, <u>if</u> an alternative supplier to Hughes and Watkins-Johnson were to be required (and if a foreign supplier were acceptable), Thomson-CSF is a potential source.

TABLE 3.7

CURRENT SHF TWTA TECHNOLOGY

MANUFACTURER	POWER (W)	EFF (%)	GAIN (dB)	BW (GHz)	COMMENTS
Hughes	20	22	46	0.25	Flown on DSCS-II, NATO III
Hughes and Watkins-Johnson	10 40	28 34	50 50	0.5 0.25	Developed for DSCS-III
Thomson-CSF	20 20	45* 45*	40 41	0.15 0.4	TELECOM-I (7.3 GHz) SPOT (8.2 GHz)

*TWT Only

* * * * *

HUGHES

C-Band (Power Level < 6 W)

INTELSAT IV/IVA, COMSTAR, WESTAR, RCA SATCOM, etc.

> 600 Tubes Flown, $>10^7$ Total Hours

X-Band

DSCS-II/NATO III 20-W Tubes

11 of 34 Failed in < 2 Years

DSCS-III 10 & 40 W Tubes

Problem with Potted Collector (40 W)

WATKINS-JOHNSON

X-Band

IDCSP 3-W Tubes, 24 Flown, $>10^6$ Hours

DSCS-III 10 & 40-W Tubes

Problems with Manufacturing Processes

Fig. 3.11. SHF TWT experience for the space segment.

Fig. 3.11 summarizes the space TWT experience of Hughes and Watkins-Johnson. Hughes is undeniably the world's leading supplier of C-band TWTs. The number of Hughes' C-band tubes flown is in excess of 600, the accumulated tube life is in excess of 10 million hours, and the number of premature tube failures very few. Consider for example, the INTELSAT-IV (I-IV) experience: as of March 1977 only one 6-watt, C-band TWT (261H) out of 168 tubes (with 3 to 6 years on orbit) had failed after 2 years of operation. Examination of the Hughes X-band (SHF) experience with DSCS-II and NATO-III TWTs shows a marked difference, i.e., of the 34 tubes flown, 11 have failed in 2 years or less. This disparity in tube reliability between C-band and X-band warrants comment. The X-band tubes have historically required higher power levels (10 W - 20 W - 40 W) than the C-band tubes (< 6 W). As a consequence of the higher power requirement at a higher frequency, the X-band tubes have higher operating voltage and temperature. In addition to being at a lower level, the power requirement for C-band tubes has remained nearly constant. As a consequence, each "generation" of tubes (i.e., I-IV, I-IVA, and I-V) incorporates improvements in and refinements to the same basic tube. Also, the quantity and scheduling of the C-band tube procurements allows for a reasonably continuous production, as compared with the three DSCS-II TWT buys during which the production line was inactive for over one year. The team expertise required to fabricate reliable space TWTs cannot be underestimated, and the low yields during production starts seem to support this premise. In examining the current Hughes experience with the DSCS-III tubes, note that there are no problems with the 10-W tube, but there is a problem with the potted collector of the 40-W tube. This collector problem evidences itself as cracks in the potting material from which corona develops, causing arc-over and tube failure. The problem with the potted collector is twofold: a collector design resulting in an entrapped (blind) potting process; and encapsulant material that may not be applicable for the higher thermal and electrical stresses. This same encapsulant was used successfully in 10-W tubes but may contribute to the failures in the 20-W tubes. A near term solution would be to redesign the collector structure and use a new encapsulant. A farther-term solution would be a new design, incorporating a

dual-depressed collector and double vacuum envelope, to provide a vacuum-encapsulated collector; this design is currently in the qualification process.

Examining the X-band TWT experience of Watkins-Johnson, note that their only substantial previous space-tube program was for the IDCSP satellites. Currently, Watkins-Johnson is having several problems with both the 10-W and 40-W tubes. The main problem is with the cathode material and processing, and has resulted in only 5000-hr. tube life. Other problems are associated with tube processing, e.g., trapped gases in the brazing operation which are later released into the vacuum envelope. With RADC, AFML and NASA assistance, several improved processing techniques were developed and have been implemented. New production is underway; the success of these modifications will be evaluated in Fall 1980.

Based on past and current experience, SHF TWT producibility and reliability continues as a concern. The tube analysis and design are mature; the problems lie in the implementation, i.e., materials, processing and testing. Technology development programs are obviously required in these areas and are being addressed within SD (AFSC/Space Division). SD/YKX has an on-going TWTA Development Program with the goal of providing broad technology support for space programs. The program is primarily directed toward long range improvements in basic TWT technology, e.g., development and testing of long-life dispenser cathodes to replace the oxide cathode for operation at EHF. YKX has also had responsibility for a TWT Improvement Program directed toward near-term advancements in the reliability and life (by a factor of two) of space TWTs. The approach has been to promote improvements in all critical areas of TWT reliability, i.e., materials, production processes and testing (e.g., potted compound study, encapsulation techniques, and life testing in a simulated space environment). Responsibility for this program has recently been transferred to YKD. Based on their DSCS-III experience and a survey of other DoD TWT programs, YKD has proposed a comprehensive TWTA Improvement Program Plan. The goal of this program is to bring about the necessary maturation of the technology base. To provide the substantial and sustained funding required, broad support is being solicited within the AF, DoD and

NASA. This program would include developments in cathode and encapsulant technology (directed primarily to the DSCS-III problem), screening and qualification and acceptance (Q&A) procedures, and test techniques. Other notable DoD programs which address the issues of tube reliability and life include the establishment of the RADC Test and Evaluation Program and the NRL Shelf Life Reliability program. These facilities will support the independent development, testing and evaluation of critical cathode technology.

B. TWT Characteristics and Technological Limits

For satellite TWT requirements at SHF, the tube characteristics are well defined and based on extensive space experience, i.e., TWTs with helical slow-wave circuits and oxide cathodes. However, there are two space TWT characteristics which are unique to the EHF band and which represent the application of new technology to the space segment. As discussed previously, the high frequency limit for helical slow-wave circuits is ≈ 40 GHz. Consequently, a 60 GHz TWT for crosslink application would require a coupled-cavity circuit. The coupled-cavity TWT will be heavier and will operate at a higher voltage than the helix TWT. As a consequence of the latter, the required power supply will exceed previously reported space-proven technology. In addition, there is little experience with coupled-cavity TWTs in a space environment (an exception being the 12 GHz, 200-watt, experimental TWT flown on CTS).

At 20 GHz and above, the second potentially unique TWT characteristic is the type of cathode. Currently, the majority of TWTs in space employ oxide cathodes, i.e., a heater, a base coating of doped nickel (> 1 mm), and an alkaline oxide coating (> 50 μm). For long cathode life (TWT life), the current density of oxide cathodes is limited to 0.2 A/cm^2. As the electron beam diameter scales linearly with operating wavelength and there is a practical limit on the beam convergence (ratio of cathode diameter-to-electron beam diameter), operation at EHF may require cathode current densities which exceed this limit. In this case, the impregnated or dispenser-type cathode (a matrix of porous tungsten impregnated with alkaline-earth aluminates) becomes necessary. The impregnated cathode can provide current densities of 0.8 A/cm^2 or greater. However, the impregnated cathode exhibits a predictable decrease

in current density with time for fixed operating parameters. In order to provide constant RF output power over the tube life, it is necessary to periodically alter the operating parameters, e.g., the Ku-band tubes to be flown on I-V will employ a programmed power supply. Life tests on impregnated cathodes have been conducted (e.g., NASA/LRC and Thomson-CSF), and further testing is planned (e.g., RADC cathode test facility). However, there is little on-orbit experience.

Fig. 3.12 presents projections of EHF TWT capability. Note that the near-term projections are based on current technology (i.e., helix circuit and oxide cathode), and represent TWT availability in the near term. The far term projections for the helix TWT are based on studies and, hence, unproven technology. The coupled-cavity TWT is considered to have long-term availability for the reasons discussed previously. Table 3.8 summarizes the projections for the frequencies of interest. Note that: a 20-watt TWT at 20 GHz has been developed and is discussed in the next section; developments at 40 GHz include a 10-watt helix TWT (Varian/RADC) as discussed in Section 3.2, and a 100-watt coupled-cavity TWT (Hughes/NASA).

C. Survey of TWT Manufacturers and Current Technology

The potential suppliers of EHF TWTs are identical to the manufacturers delineated in the SHF TWT section. Table 3.9 presents the results of a survey of 20 GHz TWT technology. The only 20 GHz tubes on orbit are the 4-watt Hughes tubes which were flown in the Japanese Communications Satellite (CS-I). A contract has been awarded to FACC for CS-II which will use the same tubes. Thomson-CSF has developed a prototype 15-watt TWT and is currently conducting flight-qualification tests. AEG-Telefunken has developed a 22-watt TWT which covers the 18.5 to 21.5 GHz band. Both the Thomson and Telefunken tubes employ dispenser cathodes. As of this writing, final contract negotiations are on-going for a dual-mode (7.5 watt/75 watt) TWT under NASA/LRC and SD/YKX funding. This tube will add to the technology base but is not directly applicable to currently proposed MILSATCOM requirements. In addition, SD/YKX has a planned 20-watt TWT development with an FY-81 start. This is a three-year program to develop a "space-qualifiable" TWT. Finally, Watkins-Johnson is developing a 20-watt TWT under internal funding. This

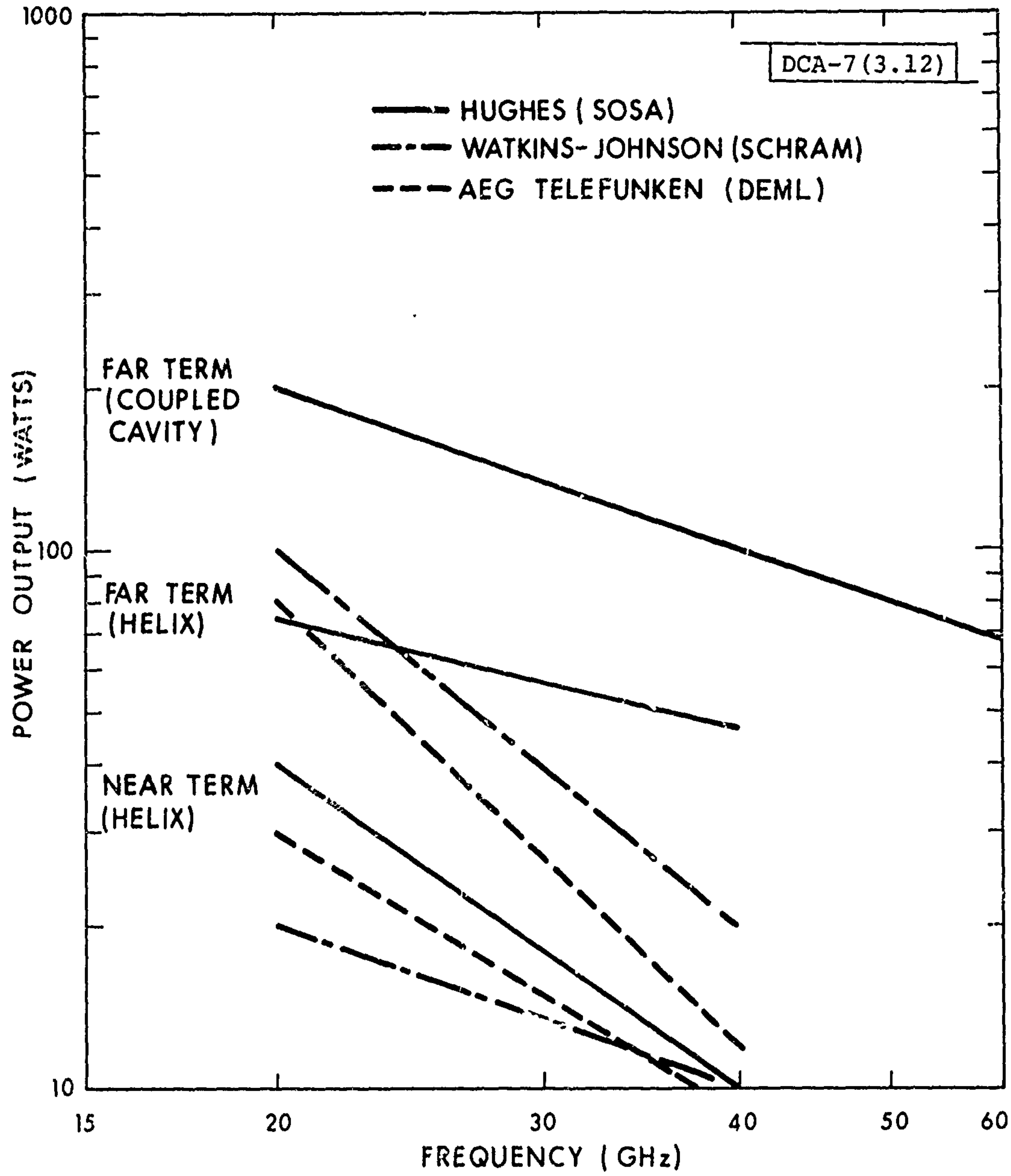

Fig. 3.12. Technological limits of EHF TWTs for the space segment.

TABLE 3.8

EHF TWT NEAR TERM PROJECTIONS*: SPACE SEGMENT

TWT CHARACTERISTICS	FREQ (GHz)	POWER (WATTS)
Helix	20	20-40
	40	10-20
	60	-
Coupled Cavity	20	(200)**
	40	(100)***
	60	(50)

*Manufacturers' estimates based on current technology.

**Far term estimates based on unproven technology.

***944H Currently in development at Hughes funded by NASA Lewis. One TWT built and tested

TABLE 3.9

CURRENT 20 GHz TWTA TECHNOLOGY

MFG/ MODEL	POWER (W)	EFF (%)	GAIN (dB)	BW (GHz)	COMMENTS
Hughes 1294H	4	17	50	1.0	Flown on CS-1
Thomson CSF	15	33*	51	1.0	Prototype Developed
AEG Telefunken	22	38*	50	3.0	Prototype Developed
----	7.5/75	30/50*	30	3.5	Contract Being Awarded NASA/LRC, SD/YKX
-----	20	--	--	1.0	Planned Development FY-81 Start, SD/YKX
Watkins-Johnson	20	40*	50	1.0	Planned IR&D Development

*TWT only

development program began in May 1980 and has a target completion date of June 1981. There is an obvious paucity of flight experience with 20 GHz TWTs.

Table 3.10 presents the results of a similar survey at 60 GHz. It is important to note that this survey was restricted to available unclassified technology. In Table 3.10, note that there are no known 60 GHz TWTs which have been flown. The only tube developments reported in the open literature are coupled-cavity TWTs (Hughes). Note that these are feasibility models, and have operating voltages and weights which are not readily compatible with satellite application. The 5-watt TWT development by RADC was originally planned to operate at 13 Kv, but was changed to 8 Kv under SD/YKX encouragement and funding to make it space compatible. The final entries in Table 3.10 are the results of a study by AEG-Telefunken which shows the theoretical feasibility of a helix TWT (3 watts) at 60 GHz.

D. Summary

At 20 GHz, space TWT experience is limited to the 4-W tubes (Hughes) flown on CS-I. The planned YKX program to develop a 20-W tube matches most currently proposed requirements, and is within the capability of current technology. As it is not usually within the YKX charter to develop devices to a "fully-operational" level, space-qualification and long-term life testing are not presently planned for this program. Consequently, extensive qualification and life testing programs will be required and must be expeditiously supported to provide an orderly transition to an EHF space segment. If a foreign supplier were acceptable, both Thomson-CSF (15 W) and AEG-Telefunken (22 W) have developed prototype 20 GHz TWTs, and would be viable suppliers.

At 40 GHz, the only relevant tube developments are the 10-W helix TWT (Varian/RADC) which is no longer planned for space application, and the 100-W coupled-cavity TWT (Hughes/NASA). The lack of emphasis on this downlink frequency band in this assessment reflects the lack of planned usage.

At 60 GHz, the RADC/YKX development will produce an engineering model (5 W) which will demonstrate the feasibility of a space-compatible TWT. The development of a space-qualified TWT at 60 GHz TWT is roughly estimated to

TABLE 3.10

CURRENT 60 GHz TWTA TECHNOLOGY

MANUFACTURER	POWER (W)	EFF (%)	GAIN (dB)	BW (GHz)	COMMENTS
Hughes	13	13	40	0.6	Feasibility Models
					Coupled Cavity
	50	18	55	0.6	Cathode Voltage=13 KV
					Oil Insulation
	100	24	55	0.6	Weight > 50 lbs
Hughes	5	14	38	0.1	Under Development
					RADC/YKX
					Coupled Cavity (8 KV)
AEG-Telefunken	3	15	35	-	Helix (5KV)
					(Design Studies)
	10	18	-	-	Coupled Cavity (10 KV)

require of the order of 5 years and $5M. Recalling the critical tolerance problems of EHF coupled-cavity TWTs for the ground segment and the producibility and reliability problems of space tubes at SHF, raises doubts about the viability of a 60 GHz TWT.

The most important issues to be addressed regarding EHF satellite TWTs are the problems of producibility and reliability. These problems persist today at SHF with its relatively mature technology. EHF TWTs will not be exempted from the current problems, but rather, will require new designs, unproven technology and more stringent manufacturing. If the necessary maturation of production technology is not developed, the DSCS-III problems will be inherited by the SPOs of future DSCS-IV, STRATSAT or TACSATCOM-II satellites. It is not possible for a single SPO to completely resolve such technological problems under normal budgetary and scheduling constraints. Consequently, broad based support for a comprehensive space TWTA improvement program must be solicited within the AF, DoD and NASA. A concerted production technology development effort must be undertaken, and must receive adequate and continuous funding. If the EHF bands are to play a major role in future MILSATCOM systems, the current planners of these systems must actively support and fund TWTA improvement programs as a necessary investment in their future systems.

IV. SOLID-STATE POWER AMPLIFIERS

4.1 Background

In the EHF TWT assessment of the previous section, it was noted that producibility and reliability of SHF TWTs for the space segment continue to be a concern. In addition to contending with the existing TWT production technology problems at SHF, the development of TWTs at EHF must address new designs, unproven technology and more difficult manufacturing. The need for developing an alternate technology is obvious and provides the impetus for assessing solid-state technology at EHF. It must be noted that advances in antenna technology may considerably reduce the requirements for high power in a single envelope and create a unique role for solid-state devices. For example, studies have indicated the desirability of time-hopped-beam and adaptive-nulling antennas to provide improved AJ performance and increased capacity. The RF control devices required to implement these antennas introduce loss which may be mitigated by using a power amplifier on each antenna element. Consequently, it is not a "winner-take-all" competition between TWT and solid-state technology with the eventual exclusion of one technology. Rather, while there will be some overlapping applications where such a competition will exist, there will be unique applications for each technology.

Since the invention of the transistor at Bell Telephone Laboratories in 1948, the advances in the theoretical basis of solid-state physics and in device processing technology have been remarkable. The variety and capability of solid-state devices has advanced to the point where thermionic devices are used in only a few highly specialized areas. In those areas where solid-state technology has supplanted vacuum tubes, solid-state devices have demonstrated a significant increase in reliability and decrease in cost. The areas in which the TWT is still almost universally used are high power applications at high frequencies, in particular, high power amplifiers (HPAs) for communications satellites. However, even this last monopoly of the TWT may soon yield to solid-state technology. Notable examples of solid-state

amplifier developments for satellite application include: a 5-W, C-Band (4 GHz) GaAs FET amplifier (developed by FACC under IR&D) for potential INTELSAT or DOMSAT application; and a 10-W, X-Band (7.5 GHz) GaAs FET amplifier (being developed by GE under SD/YKD sponsorship) for potential DSCS-III application. There is little doubt concerning the capabilities of solid-state technology at X-band and lower frequencies. The relevant issue is whether solid-state technology will have the requisite capability to be a viable candidate for application at EHF.

This assessment of solid-state technology focuses on the space segment amplifier requirements with emphasis on the 20 GHz downlink, but includes 40 GHz (downlink) and 60 GHz (crosslink) technology. In addition, devices are assessed for the ground segment at 45 GHz for possible applications requiring output power of the order of 25-to-50 watts. This assessment addresses the current state of device technology, power combining techniques, and device reliability. In addition, on-going and proposed technology development programs are surveyed, and recommendations for further development efforts are made.

4.2 Device Technology

This section addresses the current status of solid-state device technology. The assessment encompasses generic device characteristics, current commercial availability and demonstrated laboratory results. The generic devices being assessed for power amplifier application may be categorized in two major divisions; transistors and diodes.

A. Transistors

Transistors are three-terminal devices which are generally operated as two-port elements. The different types of transistors available include: the permeable base transistor, the silicon bipolar transistor, and the gallium-arsenide (GaAs) field-effect transistor (FET).

The permeable base transistor (PBT) is the newest transistor technology. The PBT was invented at Lincoln Laboratory and was first reported in August of 1979 at the Seventh Biennial Cornell Electrical Engineering Conference. The construction and operation of the device is similar to a vacuum tube triode in

that there is a very fine grid embedded in a uniformly doped GaAs channel which controls the current flow through the bulk of the channel. Simulations have shown that the maximum frequency of oscillation of this device may approach 1000 GHz. However, the capabilities of the permeable base transistor as a power device have not been explored at this time. Consequently, the PBT must be considered a potential technology for far term application and should be reassessed at a later time.

Silicon bipolar transistor technology is the oldest and best established technology considered for solid-power amplifiers. The performance and reliability of silicon bipolars has been well established, and they have been flown on several recent military satellites including LES-8/9 and FLTSATCOM. However, the upper frequency limit for silicon bipolar power transistor technology is 4 GHz, and, consequently, this technology is inapplicable to EHF.

The gallium-arsenide field-effect transistor is a newer technology than the silicon bipolar transistor but, unlike the newly discovered PBT, has demonstrated excellent performance capability up to 20 GHz. As described in the previous section, there is currently substantial interest in the power GaAs FET in both the military and commercial SATCOM communities as a replacement for the traveling wave tube amplifier (TWTA). Several programs are now underway to determine the performance and reliability of these devices for space applications. Initial indications are that the GaAs FET solid-state amplifer can achieve far greater reliability than the TWTA, while providing slightly less overall efficiency.

The results of a survey of commercially available GaAs FETs are presented in Table 4.1. Note that the upper frequency limit of these devices is 12 GHz and is indicative of the frequency extent of current commercial interest. The highest power device currently available is the Nippon Electric Company (NEC) 868898 with a saturated output power of 4 W and 5 dB of gain at 8 GHz. The highest power domestic* device is the Microwave Semiconductor Corporation

*MSC has recently been acquired by Siemens AG, Munich, Germany.

TABLE 4.1
COMMERCIAL AND LABORATORY GaAs FET AVAILABILITY

MANUFACTURER	MODEL	FREQUENCY (GHz)	POWER (W)	GAIN (dB)	T_{CH} (^oC)	EFFICIENCY (%)
MSC	88010	4-8	2.5	6	150	20[1]
	88110	8-12	2.0	--*	--	--
	88104	8-12	1.0	7	150	--
NEC	869499	11	1.7	6	175	22[2]
	868898	8	4.0	5	175	22[2]
	868496	8	2.0	5	175	23[2]
	868296	8	1.25	6	175	25[2]
FUJITSU	FLC 30	4-8	2.0	3.5	175	25[1]
TEXAS INST	MS 803	4-12	1.0	4-5	185	30[1]
RCA	MTC SERIES	6	2.0	4-5	--	15-20[1]
	MTC SERIES	12	0.5	4-5	--	15-20[1]
DEXCEL	DXL-4640A	8	0.8	--	175	22-25[1]
MITSUBISHI	MGF-2033	8	1.5	5	--	--
	MGF-2048	8	2.0	6	--	--
	MGF-2124	12	1.0	6	175	20[1]
	MGF-2148	12	1.6	5	175	16[1]
	MGF-2150	12	2.0	5	175	16[1]
	MGF-2172	7	2.8	6	175	20[1]
PLESSEY	PGAT 1000	4-8	1.1	7	--	20[1]
RAYTHEON	RPX 4302	10	0.25	8	175	--
	RPX 4305	10	0.50	7	175	--
	RPX 4310	10	1.0	6	175	--
NEC	LABORATORY	6	15.0	6.4	--	26.8[1]
	LABORATORY	8	10.5	4.5	--	11.2[1]
TEXAS INST	LABORATORY	10	5.0	--	--	--
	LABORATORY	16	1.5	--	--	--
	LABORATORY	20	0.45	--	--	--

1. POWER ADDED EFFICIENCY = $P_{out} - P_{in}/P_{DC}$

2. COLLECTOR EFFICIENCY = P_{out}/P_{DC}

*Data Not Available

(MSC) 88010 with an output power of 2.5 W and 6 dB of gain also at 8 GHz. Note that both devices have efficiency > 20%. Both Texas Instruments and RCA have catalog listings for power GaAs FETs but neither company has an aggresive marketing policy for these devices at the present time. State-of-the-art laboratory GaAs FET results are also included in Table 4.1. Simple scaling (i.e., PF^2=C) of the performance reported at C-band and X-band predicts the realizability of a 1-W device at 20 GHz. On-going development contracts directed toward achieving that goal are delineated in Table 4.2.

TABLE 4.2

CURRENT 20 GHz GaAs FET DEVELOPMENTS

MANUFACTURER	GOAL	RESULTS TO DATE	SPONSOR
Texas Instruments	1.0 W	0.45 W	AFAL
MSC	1.0 W	0.5 W 3.55 dB Gain 13% η_{pa}	Lincoln Laboratory

Current and projected GaAs FET technology is summarized in Fig. 4.1. Note that currently sponsored GaAs FET research extends only to 30 GHz, and that even the 1985 projected technology does not extend above 40 GHz. For solid state power requirements at 40 GHz and above, diode technology must be employed and is assessed next.

B. Diodes

Diodes are two-terminal devices which are generally used as oscillators or negative resistance, reflection-type amplifiers. Most of the different types of microwave diodes in use today differ more in their mode of operation than in their actual physical structure. The types of microwave diodes currently available include: Gunn, BARITT, TRAPATT, and IMPATT diodes.

The Gunn diode utilizes the negative differential mobility property of bulk GaAs to produce a negative resistance effect at microwave frequencies.

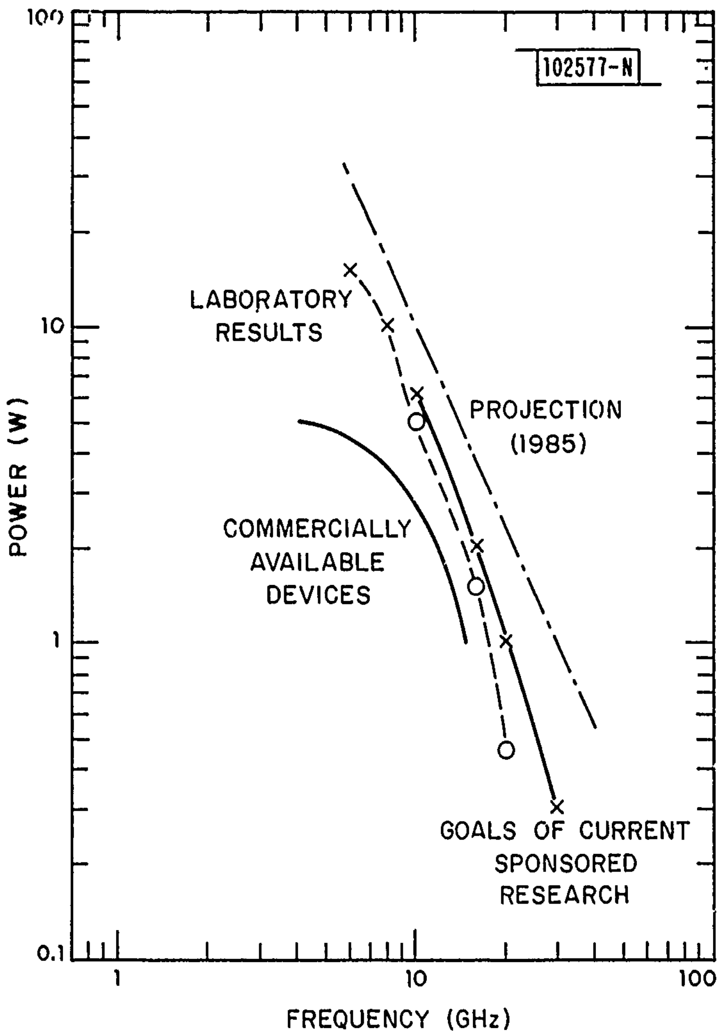

Fig. 4.1. Current and projected GaAs FET technology.

Gunn diodes produce very low noise microwave power up to ≈ 100 GHz. The maximum CW power is on the order of 1 W, but the efficiency is very low ($\approx 3\%$). A typical application of the Gunn diode is as the local oscillator in a microwave receiver, where the low noise properties of the Gunn make it ideal. The low efficiency of the Gunn diode renders it unsuitable for satellite transmitter applications.

The BARITT, TRAPATT, and IMPATT diodes are very similar in structure and fall in the general classification of "avalanche transit-time" diodes. The BARITT or BARrier Injected Transit-Time diode is characterized by low noise, low power, and low efficiency. They are typically used as low cost local oscillators in self mixing doppler radars. The TRAPATT or TRApped Plasma Avalance Triggered Transit diode is a high-power, high-efficiency mode of the IMPATT diode. The TRAPATT is capable of generating hundreds of watts of peak power in pulsed operation. The DC-to-RF conversion efficiency of TRAPATTs is 40-60%. TRAPATTs are more noisy than IMPATTs and they are typically used for low cost, high-power radars and expendable jammers. Due to their pulsed operation and high noise, TRAPATTs are unsuitable for use in satellite communication transmitters. The IMPATT or IMPact ionization Avalanche Transit-Time diode relies on the avalanche multiplication and transit time effects in bulk germanium, silicon, or gallium arsenide to produce a negative resistance effect. IMPATT diodes are at present the most powerful CW solid-state microwave sources available and, consequently, the most suitable diodes for communication amplifiers.

Silicon IMPATT diodes have been commercially available for many years, and devices have been fabricated for use up to ≈ 300 GHz. Silicon IMPATTs were flight qualified and flown on LES-8/9 to power the K-band downlink and crosslink transmitters at ≈ 38 GHz. More recently, gallium-arsenide IMPATT diodes have become commercially available. GaAs IMPATTs generally exhibit much higher DC-to-RF conversion efficiencies than silicon IMPATTs. Laboratory GaAs devices have been constructed up to 40 GHz with results that indicate usable performance beyond 60 GHz should be possible.

An extensive survey of CW IMPATT diodes was conducted. To establish the state of current commercial availability, X-band IMPATT diode technology was assessed and is presented in Table 4.3. The highest power device presently available is the Nippon Electric Co. ND8U08W-5H which is a silicon IMPATT with 4 W of output power and 10-to-13% DC-to-RF efficiency at 6-to-9 GHz. The most notable domestic device is the Microwave Associates MA-46033 which is a GaAs IMPATT with 3 W of output power and 16-to-18% DC-to-RF efficiency at 7-to-9 GHz. Since IMPATT performance specifications are usually obtained with the device used as an oscillator, the device gain is not given. Also included in Table 4.3 are notable laboratory results achieved with GaAs IMPATTs.

The commercially available CW IMPATT diodes for use at 20 GHz are listed in Table 4.4. The only devices currently listed at this frequency are silicon IMPATTs. The highest power device at 20 GHz is the Nippon Electric Company ND8W20-5H with 1.5 W at 10% DC-to-RF conversion efficiency. A laboratory GaAs device tested at 14 GHz is also shown.

The available CW IMPATT diodes for 40/45 GHz are shown in Table 4.5 and are silicon devices. The highest power device is the Nippon Electric Co. ND8N40W-1N with 0.5 W at 8% DC-to-RF conversion efficiency. The performance of laboratory devices is also presented in Table 4.5 and includes the achievement of 2.5 W at 18.6% efficiency with a GaAs IMPATT at 33.5 GHz. Appropriate scaling of this technology to 20 GHz predicts increases of a factor of 2 in efficiency and a factor of 2 to 4 in output power over currently available devices.

The available CW IMPATT diodes for use at 60 GHz are listed in Table 4.6. The highest power device is the Nippon Electric Co. ND8L60W-1T with 0.3 W of output power at 6% DC-to-RF conversion efficiency. No GaAs IMPATT performance at 60 GHz has been reported so far. However, the laboratory performance achieved at 40 GHz (Table 4.5) indicates that useful power and efficiency should be attainable at 60 GHz using GaAs IMPATT diodes.

Current and projected CW IMPATT diode peformance is summarized in Fig. 4.2.

TABLE 4.3
SHF IMPATT DIODE AVAILABILITY

MANUFACTURER	MODEL	TYPE	FREQ. (GHz)	POWER (W)	GAIN* (dB)	T_{CH} (°C)	DC-TO-RF EFFICIENCY (%)
HEWLETT PACKARD	5082-0607	Si	7.2	1.75	--	250	11
	5082-0608	Si	7.2	3.00	--	250	10.5
HUGHES	A0804	Si	7-10	0.75	--	225	5.5
VARIAN	VAO-14K1	Si	8-10	1.00	--	--	7.1
	VAO-34K	Si	6-8	1.00	--	--	7.0
NEC	ND8P08-5G	Si	6-9	1.20	--	250	5-7
	ND8S08-5H	Si	6-9	2.20	--	250	6.9-8
	ND8U08W-5H	Si	6-9	4.00	--	250	10-13.5
	V249A	Si	5.8-8.2	2.00	5-2.5	250	10-13
MICROWAVE ASSOC	MA-46207	GaAs	8.0-9.5	1.0-1.3	--	225	10-12
	MA-46033	GaAs	7.0-9.0	2.5-3.0	--	225	16-18
RAYTHEON	MS-824A	GaAs	7.1-8.5	1.80	--	225	12.5
	MS-824B	GaAs	7.1-8.5	1.00	--	225	10.0
RAYTHEON	LABORATORY	GaAs	4.8	29.5	--	--	29.5
	LABORATORY	GaAs	9.4	9.70	--	--	26.5

*SPECIFICATIONS ARE FOR DEVICES USED AS OSCILLATORS.

TABLE 4.4

20 GHz IMPATT DIODE AVAILABILITY

MANUFACTURER	MODEL	TYPE	FREQ. (GHz)	POWER (W)	GAIN* (dB)	T_J (°C)	DC-TO-RF EFFICIENCY (%)
HUGHES	47171H-0105	Si	26.5-40	0.05	--	--	--
	47171H-0110	Si	26.5-40	0.10	--	--	--
	47171H-0120	Si	26.5-40	0.20	--	--	--
VARIAN	VAO-53DI	Si	18-23	0.10	--	--	2.0
	VAO-53EI	Si	18-23	0.20	--	--	2.6
	VAO-53FI	Si	18-23	0.30	--	--	3.5
NEC	ND8M20-5G	Si	18-25	0.40	--	250	5.0
	ND8020-5H	Si	18-25	0.80	--	250	6.9
	ND8W20-5H	Si	18-25	1.50	--	250	10.0
RAYTHEON	LABORATORY	GaAs	14	3.50	--	--	16.8

*SPECIFICATIONS ARE FOR DEVICES USED AS OSCILLATORS.

TABLE 4.5

40/45 GHz IMPATT DIODE AVAILABILITY

MANUFACTURER	MODEL	TYPE	FREQ. (GHz)	POWER (W)	GAIN* (dB)	T_J (°C)	DC-TO-RF EFFICIENCY (%)
HUGHES	47103H-0105	Si	40-50	.05	--	--	--
	47103H-0120	Si	40-50	.20	--	--	--
NEC	ND8N40W-1N	Si	35-50	.50	--	250	8
HUGHES	LABORATORY	Si	40	1.70	--	--	12
RAYTHEON	LABORATORY	GaAs	33.5	2.50	--	377	18.6
	LABORATORY	GaAs	41.6	1.10	--	331	15.1

*SPECIFICATIONS ARE FOR DEVICES USED AS OSCILLATORS.

TABLE 4.6

60 GHz IMPATT DIODE AVAILABILITY

MANUFACTURER	MODEL	TYPE	FREQ. (GHz)	POWER (W)	GAIN* (dB)	T_J (°C)	DC-TO-RF EFFICIENCY (%)
HUGHES	4714H-0105	Si	50-75	.05	--	--	--
	47174-0110	Si	50-75	.10	--	--	--
	47174-0120	Si	50-75	.20	--	--	--
NEC	ND8L60W-1T	Si	50-70	.30	--	250	6
HUGHES	LABORATORY	Si	60	1.00	--	--	7

*SPECIFICATIONS ARE FOR DEVICES USED AS OCSILLATORS.

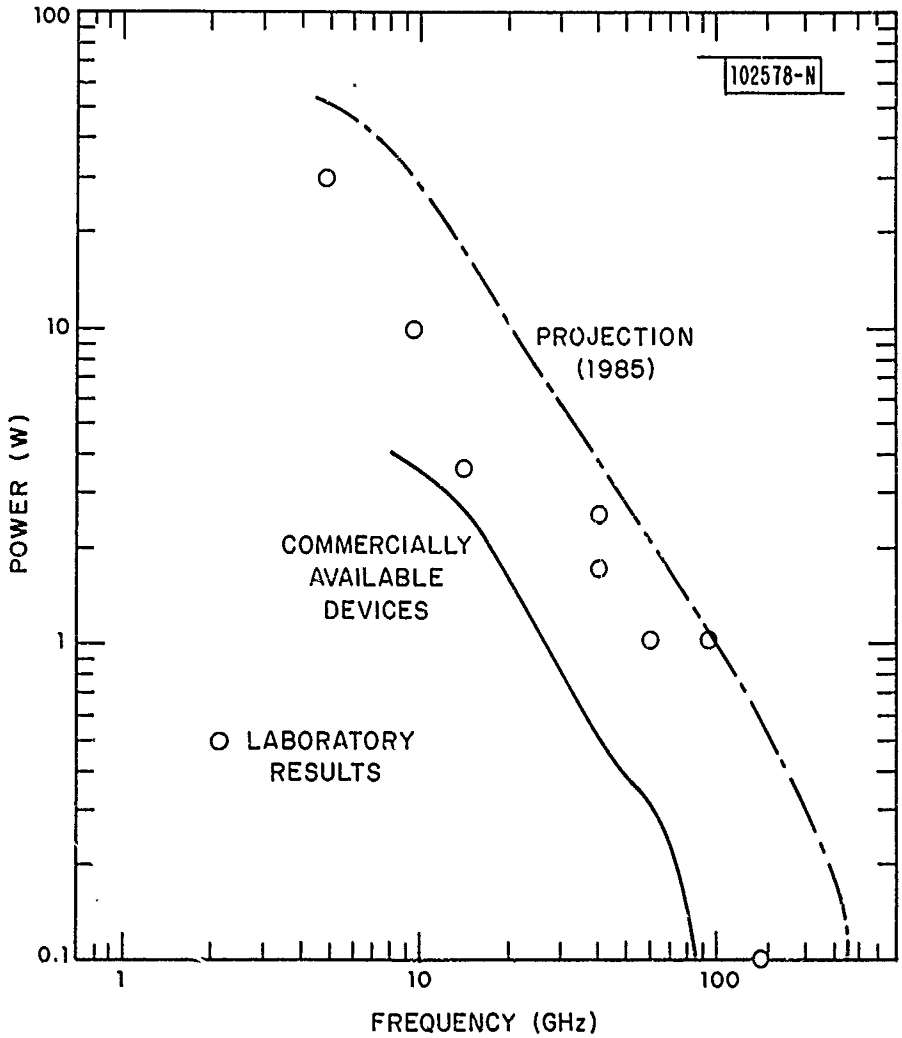

Fig. 4.2. Current and projected CW IMPATT diode technology.

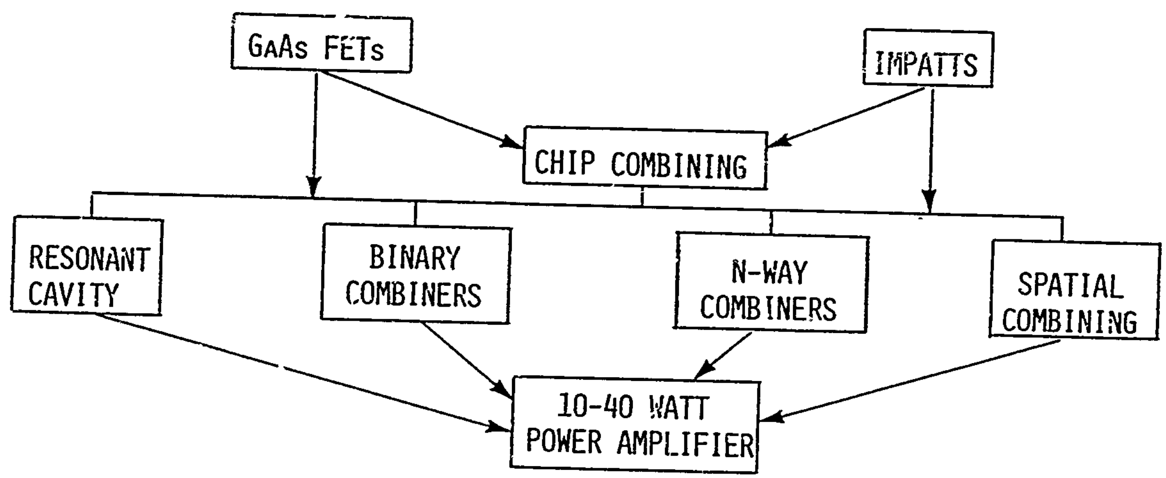

Fig. 4.3. Power combining techniques.

4.3 Power Combining Techniques

The output power available from a single transistor or diode will usually not be sufficient to meet the requirements of a satellite transmitter. For this reason, a discussion of solid-state power amplifiers must also address power combining techniques. In this section, the most commonly used power combining techniques are discussed, and their advantages and disadvantages are compared. In addition, the reduction in combined output power due to the failure or degradation of one or more amplifier modules is addressed.

Fig. 4.3 shows the paths which might be taken starting with either GaAs FETs or IMPATT diodes and ending with a 10 to 40 watt solid-state power amplifier. Two levels of power combining are shown. The first level is chip combining followed by various circuit combining techniques.

A. Chip Combining

Chip combining is illustrated in Fig. 4.4. In this example, individual GaAs FET chips are shown bonded to a common carrier. Input and output matching circuits have been provided and the entire circuit may be hermetically sealed and supplied as a single device. The Nippon Electric Company 868898 GaAs FET is an example of this technology. Note that chip combining of IMPATT diodes has the inherent difficulty of achieving proper load sharing between negative-resistance devices.

Monolithic power amplifiers have shown great promise as an alternative to chip combining. Monolithic amplifiers are constructed with the FETs and combining circuits all deposited on a single large GaAs substrate. Raytheon recently reported a 2.5-W monolithic amplifier at 9.0 GHz with four GaAs FETs combined in the power stage. The potential advantages of monolithic amplifiers are high performance, low cost and very small size. However, at the present time, the performance of more conventional circuit techniques exceeds that of monolithic designs. Furthermore, monolithic power amplifier design is a high-risk, laboratory technology at present. Significant development effort will be required in the area of fabrication technology to alter the current status, particularly at EHF.

DCA-7(4.4)

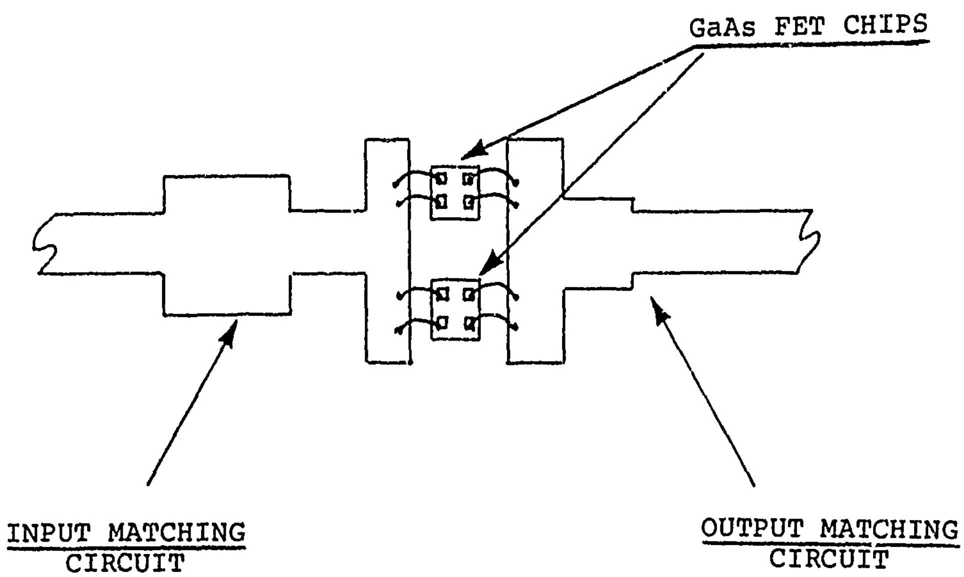

Fig. 4.4. Chip combining of GaAs FETs.

B. Circuit Combining

Individual chips or combined chips may be built into amplifier modules. These amplifier modules may be further combined using one or a combination of circuit combining techniques. Circuit combiners may be generally classified as resonant and nonresonant. Nonresonant combiners currently have performance and implementation advantages over resonant combiners, and are emphasized herein. Nonresonant circuit combining techniques include: the binary combiner, the N-way combiner, and spatial combining. These three combining techniques may be compared by means of a simple example at X-band using currently available GaAs FETs. For the purpose of comparison, the following amplifier requirements will be assumed:

Output Power	:	20.0 W
Number of Combined Stages	:	8
Input Power	:	1.0 mW
Overall Amplifier Efficiency	:	20 %

The following performance criteria will then be compared: the gain and efficiency requirements of the individual amplifier modules and the complexity and implementation of the combiner circuits.

Fig. 4.5 shows the binary combiner implemented with quadrature hybrids. (Note that each hybrid is assumed to have an insertion loss of 0.25 dB.) Each pair of amplifiers is fed by the divided power output of a quadrature hybrid connected such that the power from each amplifier pair recombines in phase. The required amplifier gain is 34.8 dB and the required amplifier efficiency is 25.6%. The circuit is fairly complex, since each combined pair of amplifiers must be combined again and so on in binary fashion until a single output is obtained. While the binary combiner is the simplest to implement, the weight, size and cumulative losses of the hybrids limit the practical number of devices to be combined to ≤ 16.

DCA-7(4.5)

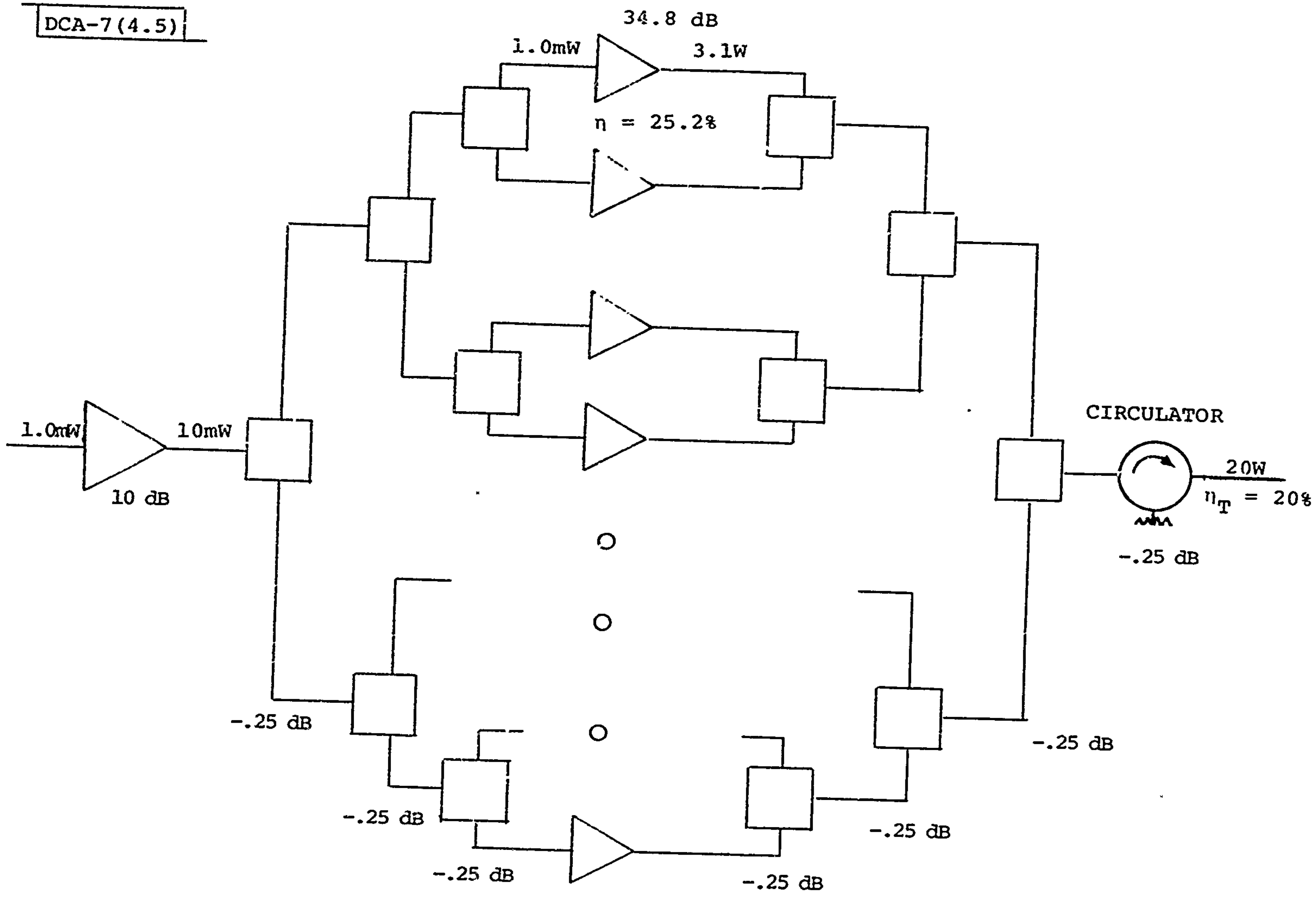

Fig. 4.5. Quadrature-hybrid power combiner.

The N-way combiner is illustrated in Fig. 4.6. A single 8-way power divider feeds the 8 individual amplifiers which are then recombined with a single 8-way power combiner at the output. Since the loss of only one combiner (assumed to be 0.25 dB) is encountered at both the input and output, the gain requirement for the amplfiers is reduced to 33.6 dB and, more importantly, the efficiency requirements for the amplifiers is reduced to 22.4%. Another advantage of the N-way combiner is that N can be any number whereas the quadrature combiner is constrained to combine 2^M stages where M=1, 2, 3, ... If insufficient power is achieved with 8 combined stages, then nine can be combined with the N-way combiner. Examples of N-way combiner technology applied to FETs at X-band include: combining 12 FETs in a radial combiner(9) with a combining efficiency of 90% over a 30% bandwidth at 8.5 GHz (the insertion loss of the 12-way combiner = 0.25 dB); combining 6 FETs in a planar combiner(10) with a combining efficiency of 80% over a 40% bandwidth at 10 GHz. In both cases, the port-to-port isolation of the combiner ranges from 14-to-22 dB, and the combining efficiency includes the variation in phase and amplitude between individual amplifier modules. While the N-way combiner has considerable advantage in size and weight over the binary combiner, the N-way combiner is more difficult to design and to implement, and technology development will be required at EHF.

The spatial combiner is shown in Fig. 4.7. The individual amplifiers are fed from an 8-way power divider. Each amplifier drives its own antenna element, such as a waveguide horn. The power through each amplfier is phased such that the total power radiated by the antenna recombines in an additive manner. Here, the power combining is done in free space, thus eliminating the loss in the power combiner. The gain requirement for the spatially combined amplifiers in this example is 33.4 dB and the efficiency requirement has been further reduced to 21%. The spatial combiner results in the simplest amplifier circuit, but requires a compatible antenna design.

Another circuit combiner of interest is the resonant cavity combiner. The resonant cavity is a waveguide cavity into which several devices are coupled by means of the electromagnetic fields in the cavity. This method has been

DCA-7(4.6)

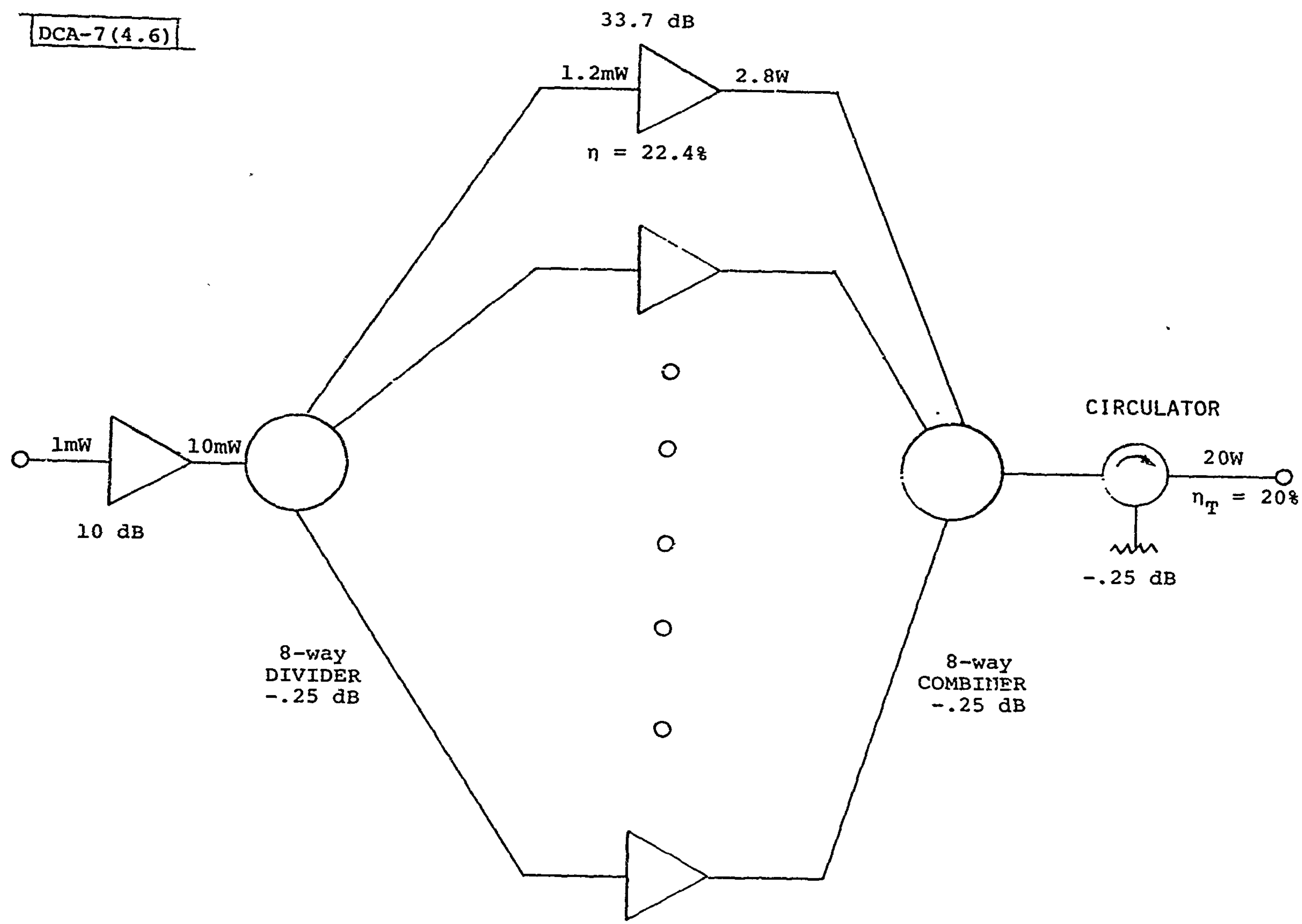

Fig. 4.6. N-Way power combiner.

DCA-7(4.7)

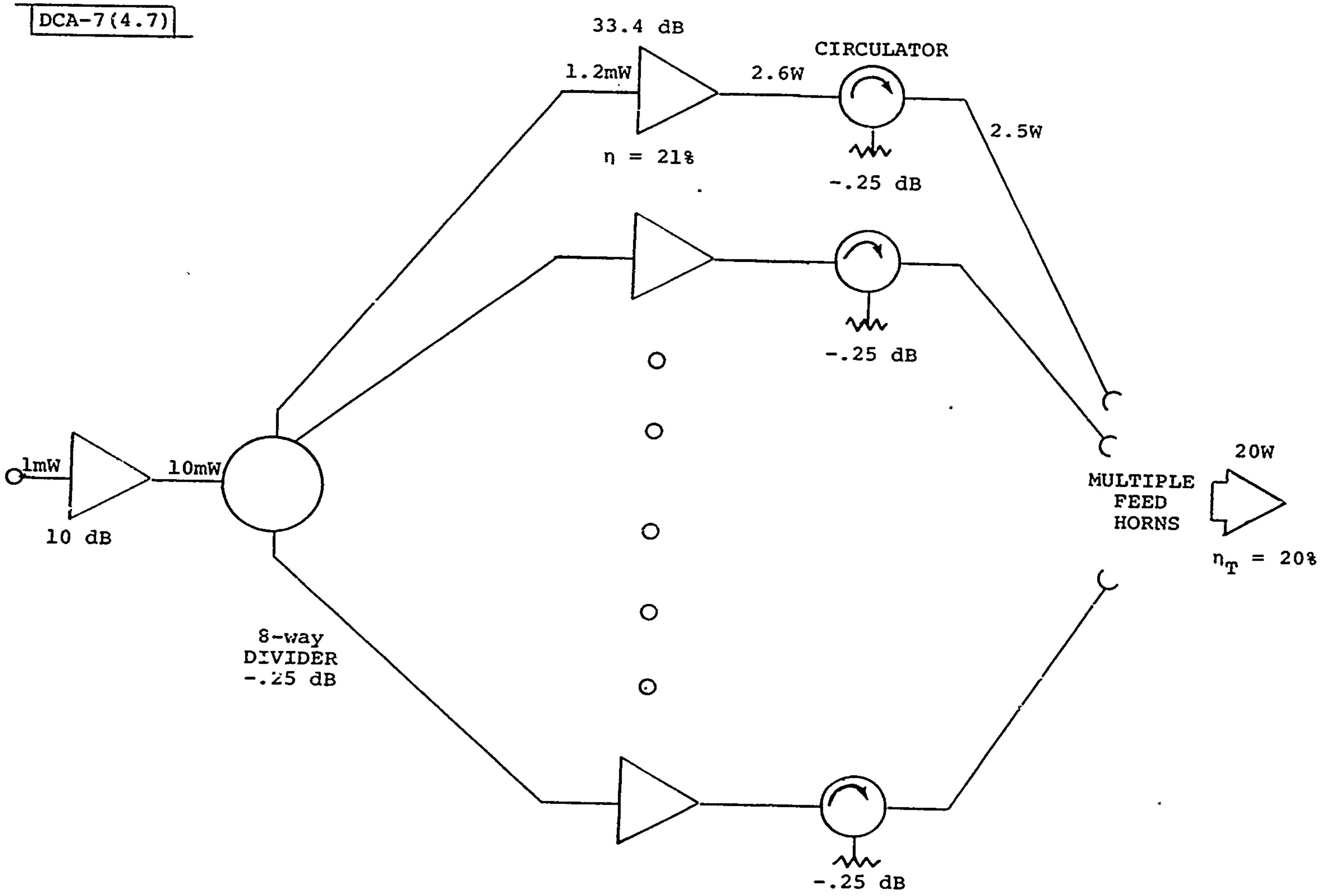

Fig. 4.7. Spatial power combining.

successfully used in both cylindrical and rectangular cavities to power combine the outputs of several injection-locked IMPATT diode oscillators. The combining losses are very low and the entire package can be made small and relatively low in mass. The disadvantages of the resonant combiner are relatively narrow bandwidth compared with nonresonant combiner circuits discussed previously, and the possibility of catastrophic failure modes. These are addressed in the next section. An additional disadvantage at EHF is the limitation on the number of diodes which can be combined in the cavity. The cavity dimensions decrease linearly with increasing frequency, but there are limits on the minimum size of the diode package and associated circuit. Consequently, cavity combiners at EHF are limited to combining ≈ 10 diodes.

C. Degradation Characteristics of Power Combiners

The three nonresonant circuit combiners which have been discussed all exhibit the property of graceful degradation. If one amplifier module out of N combined modules fails, the total power output does not go to zero, but rather degrades in a predictable manner. Fig. 4.8 shows the degradation in output power as a function of the number of active input modules for a 12-way, a 10-way, and a 2-way power combiner. As shown in Fig. 4.8, with one inoperative stage out of twelve, the total output power is degraded to 84% (-0.76 dB). Furthermore, output power degrades to 81% (-0.9 dB) for one inoperative stage out of ten, and to 25% (-6.0 dB) for one inoperative stage in a 2-way combiner. Fig. 4.9 shows the degradation in total output power caused by the partial degradation of power from one input module.

The sensitivity of output power to phase mismatch between the power combined amplifers is shown in Fig. 4.10. A degradation in output power of 79% (-1 dB) requires a phase mismatch of over 50° for a 2-way combiner. More than 100° of phase mismatch can be tolerated with less than 1 dB of power degradation for the 10-way and 12-way combiners.

In Figs. 4.8, 4.9 and 4.10, it is assumed that the other N-1 input modules are operating at their nominal power level and in phase, i.e., that they are uneffected by the degradation occurring on the Nth module. This assumption is strictly valid only if the isolation between individual amplifiers is

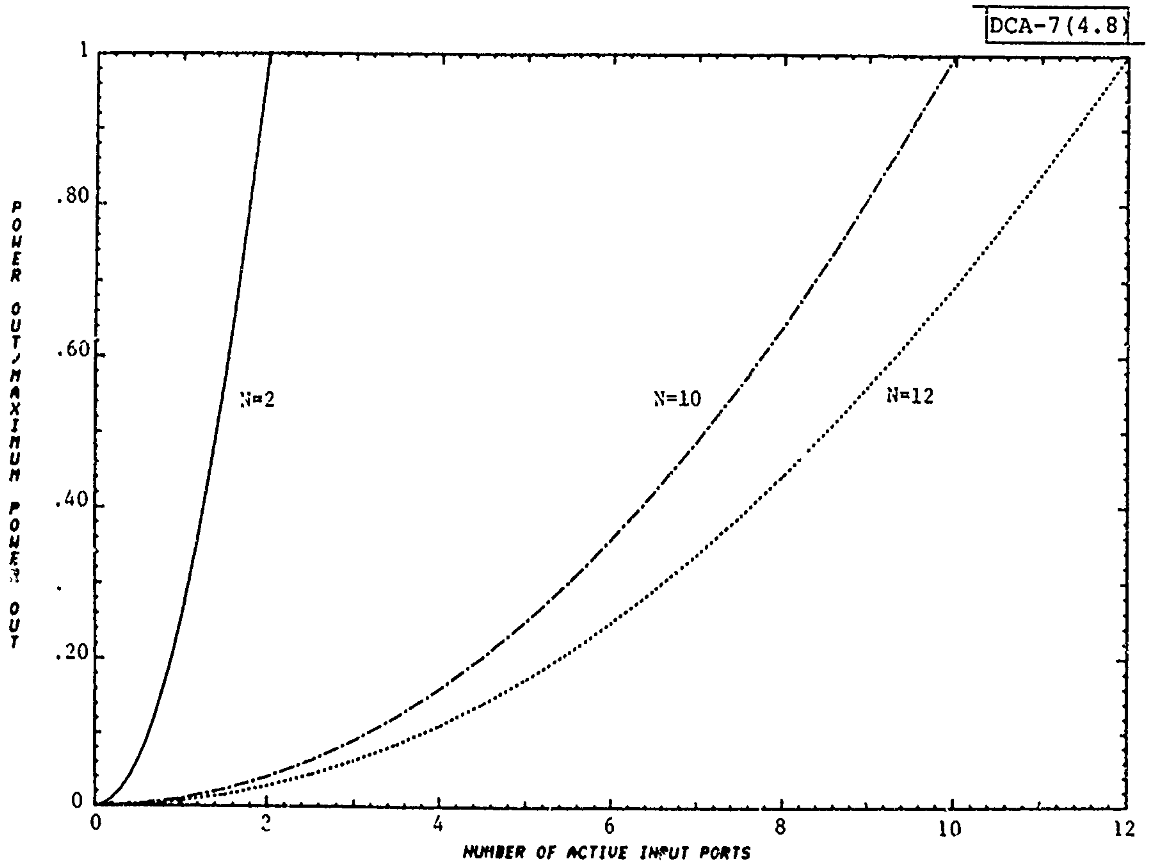

Fig. 4.8. Degradation in output power of a nonresonant combiner as a function of the number of operating amplifiers.

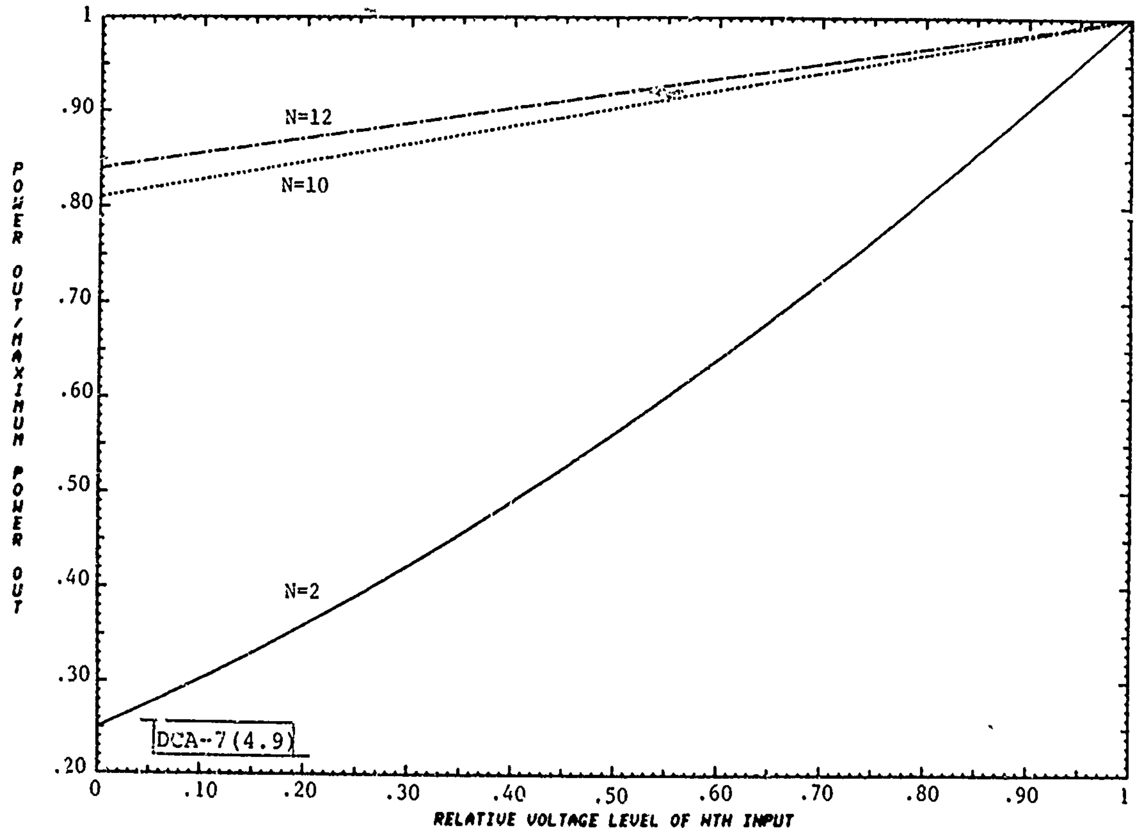

Fig. 4.9. Degradation in output power of a nonresonant combiner as a function of the relative amplitude of one amplifier.

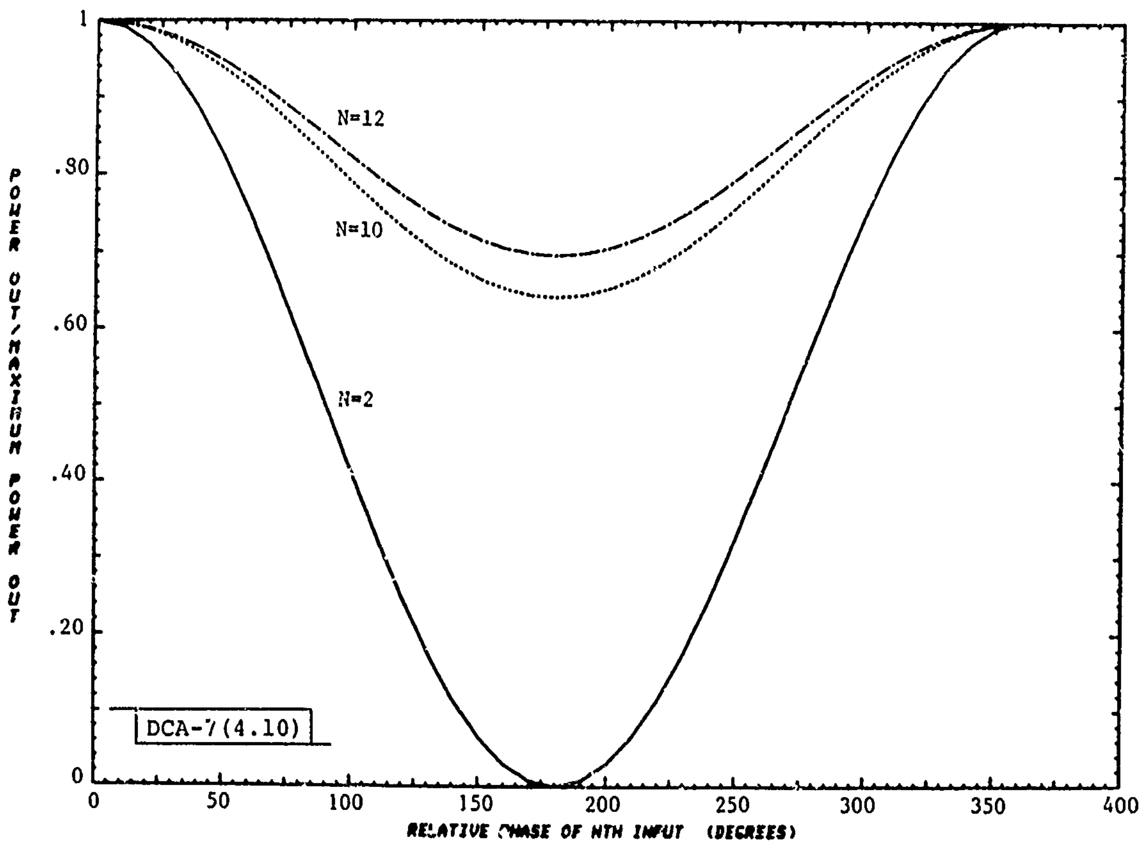

Fig. 4.10. Degradation in output power of a nonresonant combiner as a function of the relative phase of one amplifier.

infinite. In practice, combiner circuits can be implemented with 20 dB isolation between amplifiers. Consequently, the actual degradation would closely approximate the ideal estimates given in the figures. A 2Nx2N dimensional mathematical analysis of a specific combiner design and amplifier failure would be required to determine all of the possible variations in amplitude and phase of all N input ports.

As previously stated, one of the disadvantages of the cavity combiner is the possibility of catastrophic failure modes, as compared to the graceful degradation of nonresonant combiners. The catastrophic failure modes result because the loss of a single diode (IMPATT diodes are used in cavity combiners) may detune the cavity such that the remaining diodes cannot sustain oscillation. Although the observed failures in cavity combiners are not always catastrophic, the degradation is typically unpredictable.

A summary of the advantages and disadvantages of the various circuit combining techniques is given in Table 4.7.

4.4 Solid-State Transmitters

A. 7.5-GHz Transmitter

This section presents strawman solid-state transmitter designs which are capable of meeting proposed satellite HPA requirements. The purpose of these examples is to assess the capability of current technology to satisfy such requirements. Although these transmitter designs are not optimized, they adequately serve the purpose of demonstrating those areas requiring technology improvements.

A transmitter which would provide output power of 20 W at 7.5 GHz is shown in Fig. 4.11. Twelve power amplifier (PA) modules using GaAs FETs have been combined using a 12-way combiner. The twelve modules are driven by another identical PA module which is preceeded by three low-level, preamplifier stages. The PA modules have an overall gain of 10 dB, and the final stage is assumed to have 30% power-added efficiency. (This performance has been achieved by General Electric Company in the program to develop a solid-state amplifier (SSA) as a replacement for the 10-W TWTAs on DSCS III.) The overall efficiency of the 20-W transmitter is 22% and the conditioned DC power

DCA-7 (4.11)

Efficiency of Final Stage	30%
Overall Gain	43 dB
Overall Efficiency	22%
Total DC Power	90.4 W
Power Dissipated	70.4 W
Weight	3 - 5 lbs.
Active Devices	29

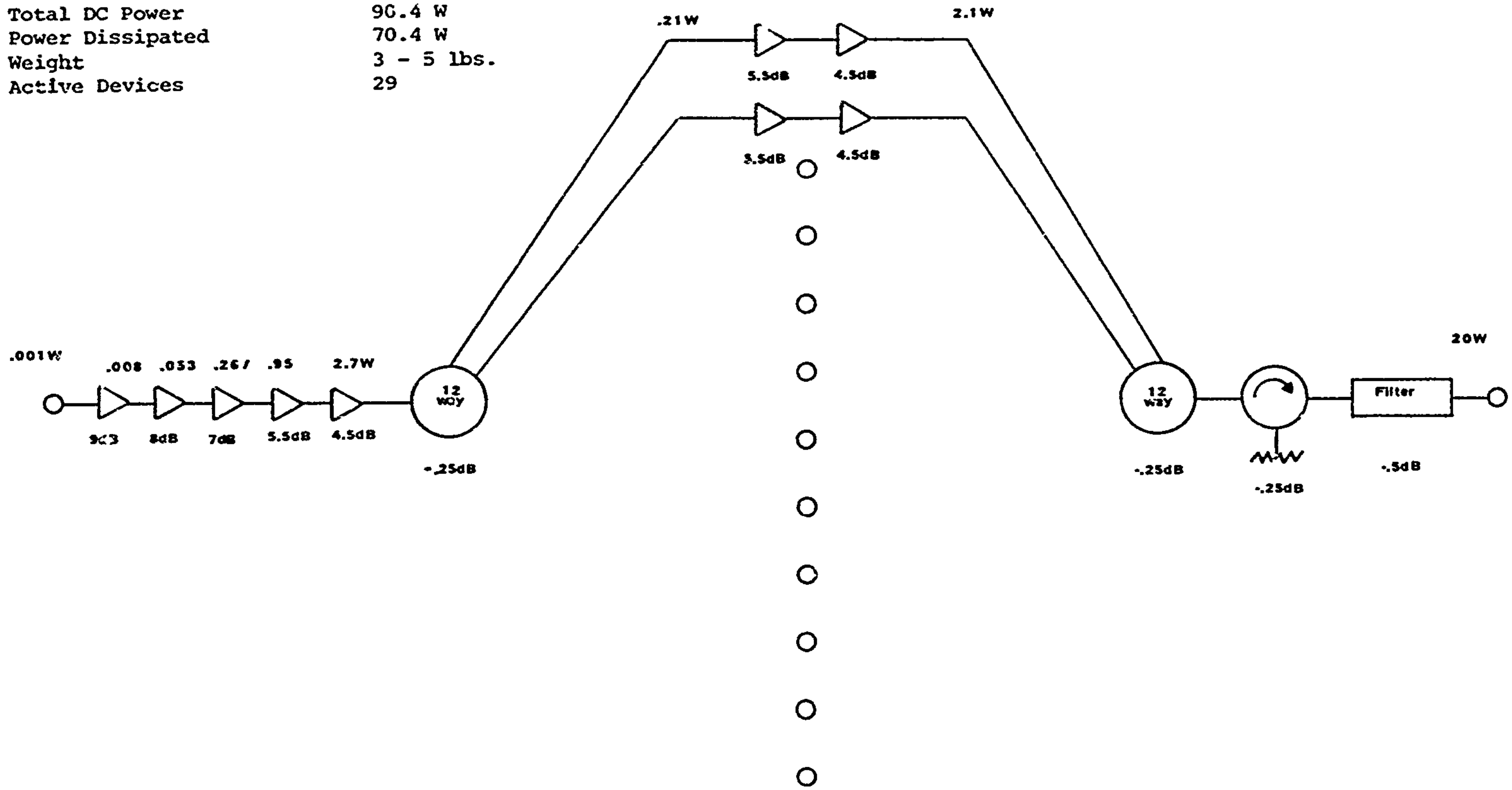

Fig. 4.11. 20-W, 7.5 GHz GaAs FET transmitter.

TABLE 4.7

SUMMARY OF POWER COMBINING TECHNIQUES

TYPE	ADVANTAGES	DISADVANTAGES
NON-RESONANT	Broad Bandwidth Amplifiers Isolated Graceful Degradation	
Binary Combiner	Ease of Implementation	Highest Insertion Loss Largest Size and Weight Limited to < 16 Devices
N-Way Combiner	Lower Insertion Loss Smaller Size and Weight Useful for Any Value of N	Difficult to Implement Requires Development
Spatial Combining	Lowest Insertion Loss Ease of Implementation	Requires Compatible Antenna Design
RESONANT	Highest Efficiency Smallest Size and Weight	Catastrophic Failure Narrow Bandwidth Limited to ~ 10 Devices

required is 90.4 W. The weight is estimated to be 4 to 5 lbs. based on an estimate by General Electric Company of 3.5 lbs. for the 10-W SSA. It was assumed that doubling the power would not double the weight since there are many components which are common to both amplifiers.

A transmitter which could provide 32 W at 7.5 GHz is shown in Fig. 4.12. Two PA modules identical to those in the 20-W design have been combined using quadrature hybrids. Ten of the quadrature-combined modules have then been combined using a 10-way combiner. The ten modules are driven by another identical PA module which is driven by a four-stage preamplifier. In order to eliminate the quadrature combiners, a 20-way combiner would be necessary which, although technically feasible, would present a formidable mechanical design task at 7.5 GHz. The 32-W transmitter has an overall efficiency of 20.8% and requires 154 W from the DC power conditioner. The weight estimate is $\approx$ 1 lb. heavier than the 20-W transmitter because of the larger circuit-board area required for the quadrature combined modules. Note that the efficiency of the complete transmitter is > 20%, and is $\approx$ 25%, if the insertion loss of the output circulator and filter is not attributed to the amplifier. In this latter case, the solid state tranmitter has an efficiency comparable to current TWT technology, e.g., 28% for the 10-W, DSCS-III TWT.

B. 20-GHz Transmitter

A 20-GHz transmitter with an output power of 21.4 W is shown in Fig. 4.13. This transmitter is based on a GaAs IMPATT diode which can produce 2 W of RF power at a DC-to-RF conversion efficiency of 18%. Lincoln Laboratory currently has a contract with Varian to develop this device for the Laboratory's Current System MILSATCOM technology development program. Quadrature hybrid combiners have been used at 20 GHz for two reasons. First, as shown in Fig. 4.14, a quadrature hybrid is used to power combine two IMPATT reflection amplifiers and at the same time provide steering for the input and output power of these 1-port amplifiers. This configuration could be constructed entirely in microstrip which would keep weight and size to a minimum. Circulators would be an alternative to quadrature hybrids for power steering, but power combiners would still be necessary. The second reason

DCA-7(4.12)

Overall Gain	45 dB
Overall Efficiency	20.8%
Total DC Power	153.7 W
Powar Dissipated	121.7 W
Weight	4 - 6 lbs.
Active Devices	48

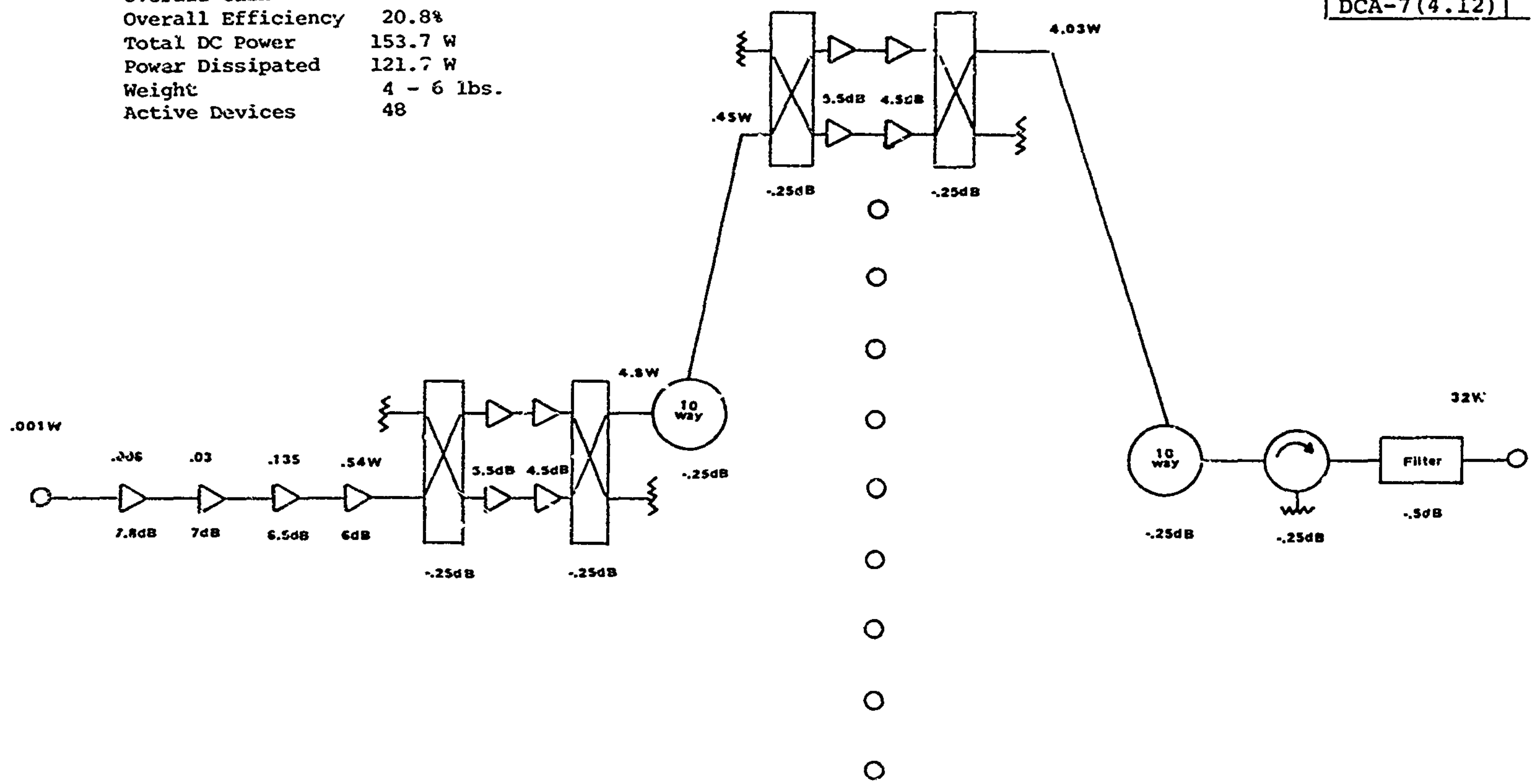

Fig. 4.12. 32-W, 7.5 GHz GaAs FET transmitter.

DCA-7(4.13)

Diode Efficiency	18%
Overall Gain	39 dB
Overall Efficiency	11.5%
Total DC Power	186 W
Power Dissipated	164.6 W
Weight	5 - 10 lbs.
Active Devices	38

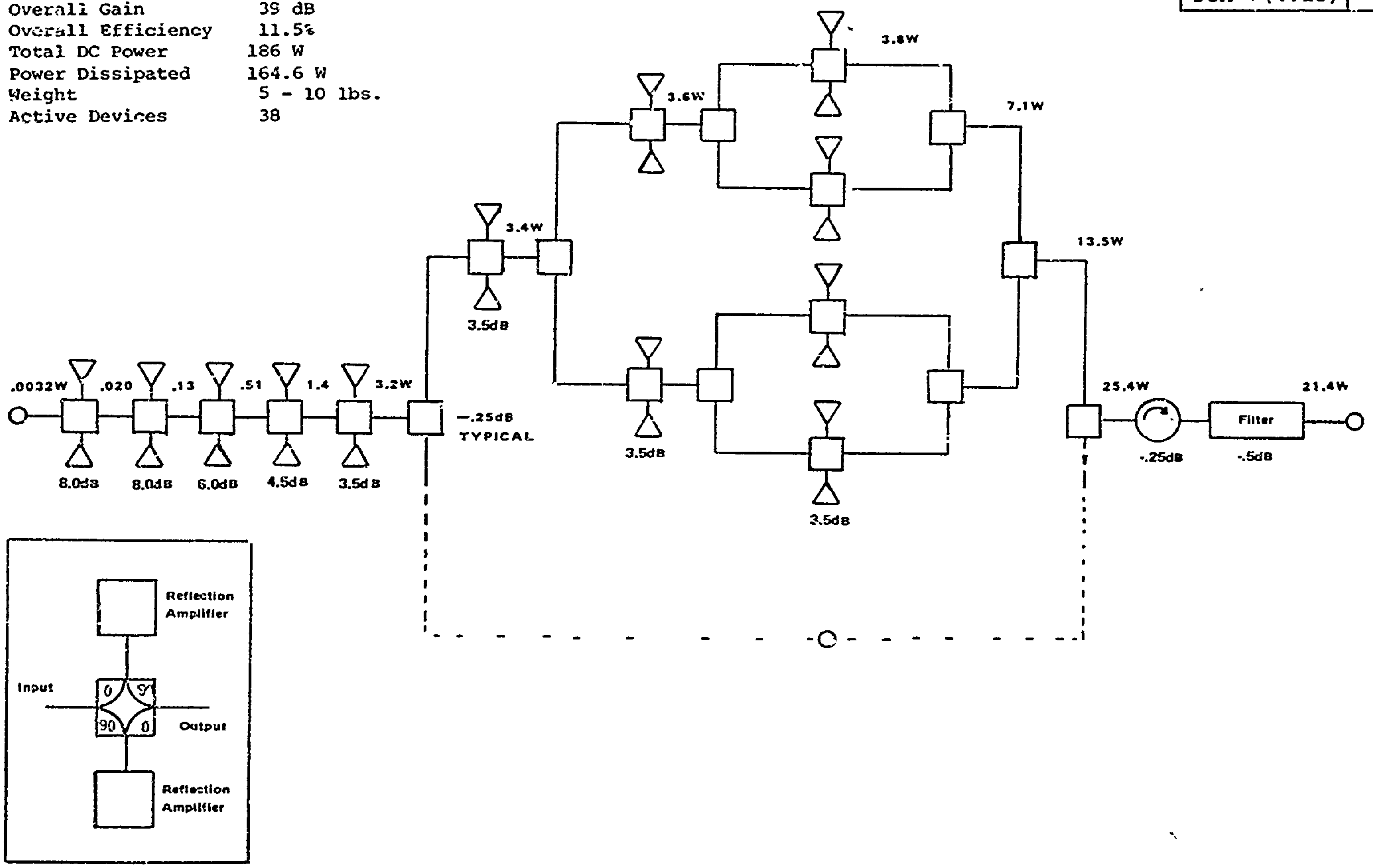

Fig. 4.13. 20 GHz GaAs IMPATT transmitter.

DCA-7(4.14)

Diode Efficiency	5%
Overall Gain	32 dB
Overall Efficiency	3.3%
Total DC Power	61.4 W
Power Dissipated	59.4 W
Weight	6 - 12 lbs.
Active Devices	22

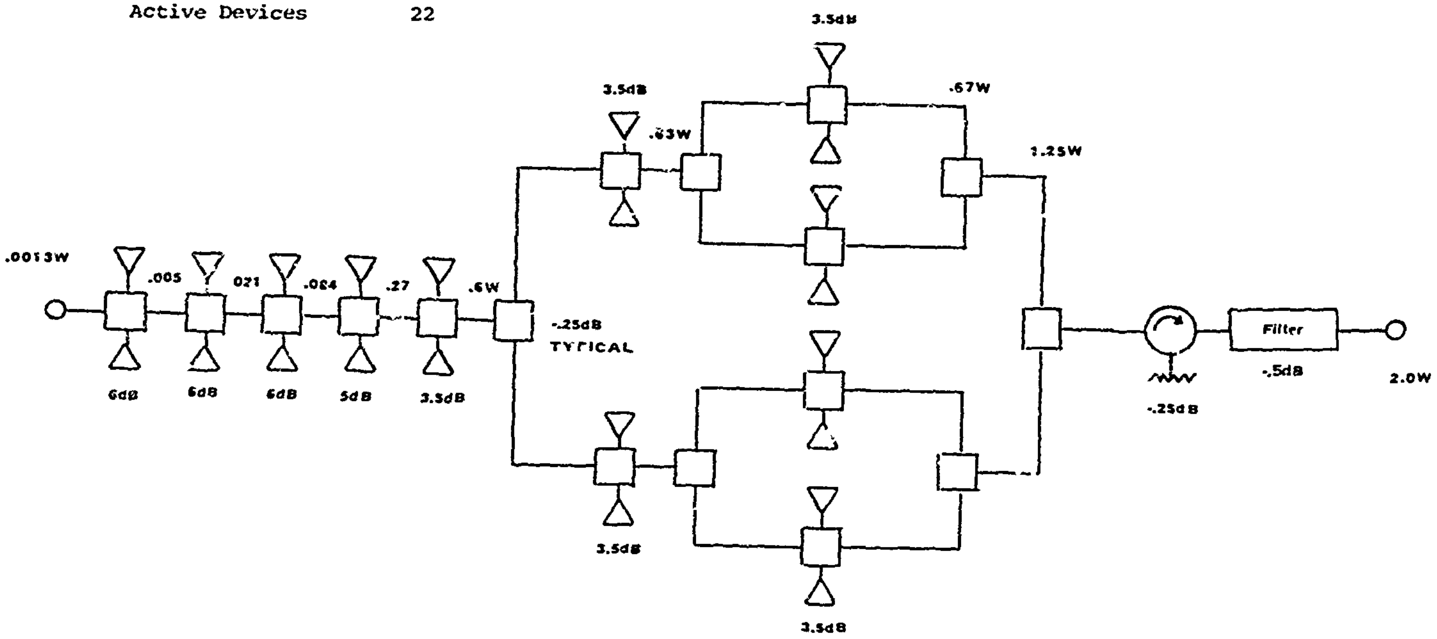

Fig. 4.14. 60 GHz Si IMPATT transmitter.

quadrature hybrids have been used is for ease of construction. Sixteen individual reflection amplifiers are combined to produce 21.4 watts at the antenna feed. At 20 GHz, a sixteen-way combiner that would provide the necessary isolation between amplifiers may be difficult to obtain. Quadrature hybrids are felt to be lower risk solutions at this time. Following the first four driver stages, the amplifier modules are identical. The overall efficiency of the 20-GHz transmitter is 11.5% and the conditioned DC power required is 186 W. Due to the large heat dissipation in the transmitter, the weight has been estimated at between 5 and 10 lbs. to provide the mass and surface area necessary to transfer and distribute the heat into the spacecraft structure.

A resonant cavity combiner could have significant performance advantages over the amplifier shown in terms of efficiency and weight. However, the inherent problems associated with the resonant cavity combiners, i.e., narrow bandwidth and catastrophic failure modes, would have to be addressed. At this time, resonant cavity combiners are viewed as a much higher-risk technology. Significant improvement in efficiency can be obtained with a spatially-combined design. If the power combiners from the final stages of the amplifier shown in Fig. 4.14 are eliminated, the overall efficiency increases to 16.8% for the same RF power output, resulting in a decrease in the required conditioned DC power input from 186 W to 127 W. Further improvements in the efficiency of the solid-state devices and combiner circuits are required to provide performance comparable to TWT technology at 20 GHz (present efficiency > 25%).

C. 60-GHz Transmitter

A 2-W, 60-GHz crosslink transmitter is shown in Fig. 4.14. The amplifier shown is similar to the 20-GHz IMPATT transmitter with eight stages. The individual diodes are required to produce ≈ 350 mW of RF power with 5% DC-to-RF conversion efficiency. This corresponds approximately to the highest power silicon IMPATT commercially available at the present time. The overall efficiency is 3.3% and 61.4 W of power is required from the DC power conditioner. Since the construction would probably require waveguide, the

weight has been estimated at 6 to 12 lbs. Following the first four driver stages, the amplifier modules are identical, which reduces the transmitter design task significantly. It is obvious that the need for improved device efficiency is most critical at 60 GHz. GaAs technology, already demonstrated at 40 GHz, affords the opportunity for such improvements.

The transmitter design examples presented indicate the need for increased device efficiency and power output, and improved combining circuits, particularly at EHF. Several such programs are in progress and are delineated in the following section.

D. Development Schedule

A strawman schedule for solid-state transmitter development based on an assumed 1987 launch is shown in Fig. 4.15. As shown by the schedule, device qualification efforts should begin in 1981 to provide qualified devices for engineering model development in 1983. Brassboard development can take place prior to 1983 using commercial grade devices. Note that to make a 1987 launch there is approximately one year before device selection must be made and device qualification started. The point being made is that the advanced device development of the next 2 to 3 years will be in support of a satellite to be launched in the 1990 time frame.

4.5 Advanced Development

It is generally accepted that improvements in solid state technology are required at EHF to attain the level of performance currently enjoyed at lower frequencies. Several DoD programs are in progress which are directed toward all aspects of the technology. These advanced development efforts are summarized herein.

A. 7.5 GHz Development

A summary of current solid-state development efforts at 7.5 GHz is given in Table 4.8.

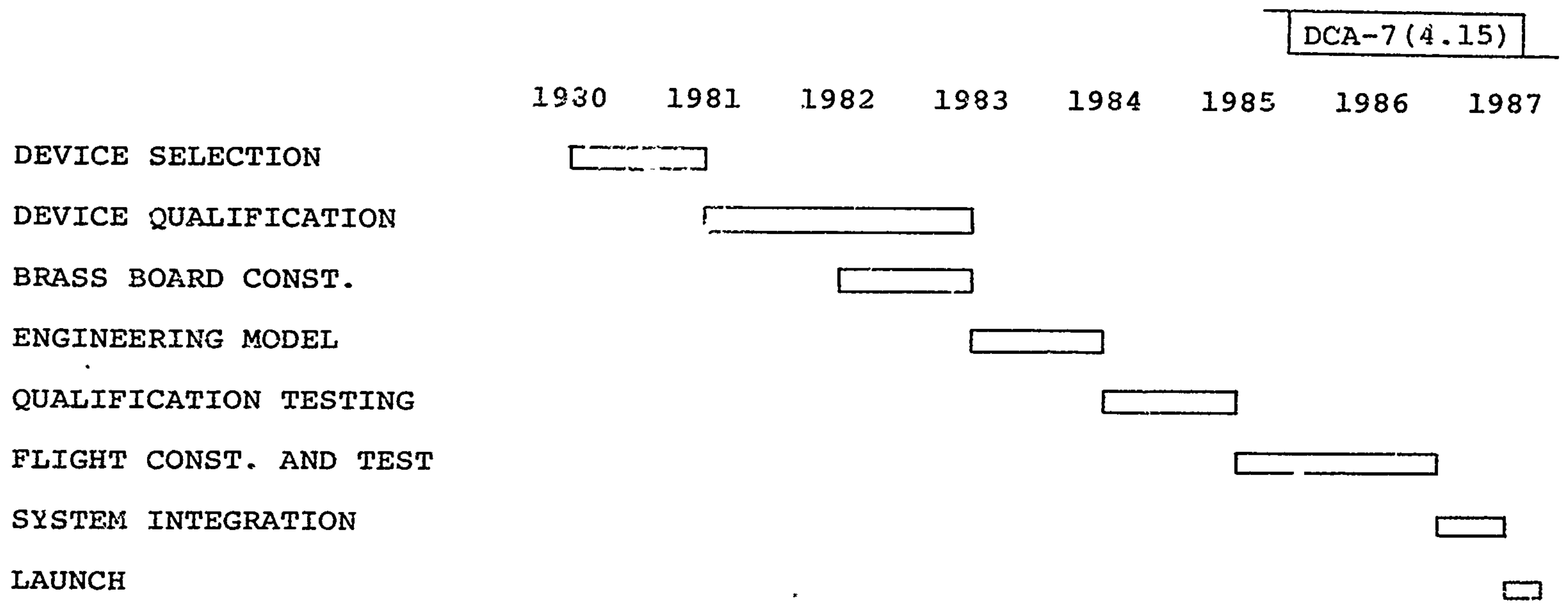

Fig. 4.15. Solid-State amplifier development schedule.

TABLE 4.8

SOLID-STATE DEVELOPMENTS AT 7.5 GHz

PROGRAM	GOALS	VENDOR	SPONSOR
Risk Reduction	High Reliability 40-44% Eff.	MSC/JPL	SD/YKX
Active Aperture	> 40 W	JPL/Motorola	SD/YKX,AFAL
SSA for DSCS-III	10 W	GE	SD/YKD
Power Combining	Technology	Raytheon	AFAL

The risk reduction program and SSA for DSCS-III should have significant impact on the viability and acceptability of solid-state technology. The active aperture program is intended to extend the limits of solid-state power and to evaluate the performance degradation due to differences in the amplitude and phase of the individual modules. The power combining program is a technology development program to analyze and assess generic combiner techniques and transmission media, and will provide broad support for future SSA development.

B. 20 GHz Developments

The current solid-state development at 20 GHz is presented in Table 4.9.

TABLE 4.9

SOLID-STATE DEVELOPMENTS AT 20 GHz

PROGRAM	GOALS	VENDOR	SPONSOR
GaAs FET Technology	1 W	TI	AFAL
GaAs FET Development	0.5 W	MSC	Lincoln Lab
GaAs IMPATT Technology	4-6 W		AFAL-SD/YKX
GaAs IMPATT Development	2 W 18% η_{PA}	Varian	Lincoln Lab
GaAs IMPATT Development	4 W 20-25% η_{PA}	Raytheon	Raytheon

Note in Table 4.9 that there are "Technology" programs and "Development" programs. The technology programs essentially provide the basis for future device development. For example, the AFAL GaAs FET technology program addresses materials research, device profiles, circuit designs and fabrication techniques. However, technology programs do not usually emphasize achieving the specified performance goals. Consequently, development programs are required to provide devices for specific applications. Both types of development are required, in particular at EHF.

C. 40-45 GHz Developments

The current solid-state developments at 40-45 GHz are shown in Table 4.10.

TABLE 4.10

SOLID-STATE DEVELOPMENTS AT 40-45 GHz

PROGRAM	GOALS	VENDOR	SPONSOR
40 GHz IMPATT Amplifier Development	10 W 30 dB Gain 100 MHz BW	TRW/ Hughes/ Raytheon	AFAL
Q-Band Solid-State Amplifier Development	Diodes 2W, 12% Eff 225°C	Hughes	NOSC
	Combiners 6W		
	Transmitter 10W 5%BW 44 GHz		
Impatt Diode Technology 40-100 GHz	GaAs 2W, 20% Eff	FY 81 Award	AFAL
	Reproducibility Reliability		

The IMPATT amplifier program is being carried on at TRW using Hughes silicon IMPATTs and, if time permits, Raytheon GaAs IMPATTs. The Q-Band solid state amplifier program has three phases as shown in Table 4.10. The first phase is for diode development and will be followed by power combining to the 6 W level. The final phase is for the development of an engineering model transmitter having the specifications shown. The IMPATT diode technology program is a follow on to the work recently completed at Raytheon and will be awarded in FY 81.

D. 60 GHz Developments

The current solid-state developments at 60 GHz are presented in Table 4.11.

TABLE 4.11

SOLID-STATE DEVELOPMENTS AT 60 GHz

PROGRAM	GOALS	VENDOR	SPONSOR
Amplifier Development	2 W	Hughes	AFAL-SD/YKX
GaAs IMPATT Diode Development	1 W 15% Eff.	Raytheon	Raytheon

The GaAs IMPATT diode development by Raytheon is an in-house effort which is planned for the near future. The goals are based on the performance of devices developed at 40 GHz (Table 4.5). The increased efficiency of GaAs IMPATTs would significantly increase the viability of 60 GHz transmitters.

4.6 Reliability

It is generally accepted that TWTAs will provide higher output power with higher efficiency than solid-state technology. The distinct advantages of solid-state technology are higher reliability and longer life. However, solid-state development efforts are typically directed toward higher performance, particularly higher output power. Consequently, in many cases, reported achievements in output power are achieved under operating conditions (i.e., junction or channel temperatures) which are not compatible with high

reliability. In all cases, the efforts directed toward reliability testing of solid-state devices significantly lag the advanced performance developments. It is important that these efforts be balanced to insure that the main advantages of solid-state technology - high reliability and long life - are in fact realized.

Reliability studies which have been reported for GaAs FETs and IMPATT diodes are listed in Table 4.12. Several of these studies are currently in progress with only preliminary results reported to date. However, the available data is very encouraging, i.e., in the studies listed, the MTTF (Mean-Time-To-Failure) is > one million hours. Note that the Bell Telephone Laboratory study included extensive device screening tests - a necessary adjunct to reliability tests. As extensive reliability tests would have to be made for any solid-state devices selected for space application, the advanced device developments in the next several years will provide the basis for the flight-qualified amplifiers of the late 1980s/early 1990s.

4.7 Summary

A. Device Technology

There are no commercially available GaAs FETs at 20 GHz or above. The currently demonstrated laboratory performance is 0.5 W at 20 GHz; the on-going development programs are directed toward achieving 1 W at 20 GHz, and should receive continued support. Useful power GaAs FETs at 40 GHz or above will not be available in the near term, if ever. IMPATT diodes have the requisite high frequency performance to provide useful devices at 60 GHz and above. However, this capability is not reflected in current catalog devices. Based on the current commercial availability of IMPATT diodes, the output power and efficiency are too low to provide suitable satellite transmitters. Only with advanced device developments can IMPATT HPAs be competitive with TWTs. Based on present laboratory results current IMPATT technology can provide such improved devices.

The current and projected availability of solid-state devices is summarized in Table 4.13. The "present" columns contain the performance of devices which are currently listed in catalogs or have been developed under contract. These devices have utility in conducting reliability and life

TABLE 4.12

RELIABILITY STUDIES OF SOLID-STATE POWER DEVICES

DEVICE	COMPANY	RESULTS TO DATE
5W, 4 GHz GaAs FET	BTL	7.5×10^6 - 5×10^8 hrs MTTF at 110°C Channel Temperature
7.5 GHz GaAs FETs	GE	SSA is more reliable than TWTA - assuming single transistor failure causes catastrophic failure of amplifier
38 GHz Silicon IMPATTS	LINCOLN LAB	10^6-10^8 hrs MTTF at 200°C junction temperature
1 W, 8 GHz GaAs FETs	MSC	4×10^6 hrs MTTF at 125°C Channel Temperature
1.25 W, 40 GHz Silicon IMPATTS	HUGHES	$\approx 10^6$ hrs MTTF at 225-250°C Junction Temperature
1.0 W, 60 GHz Silicon IMPATTS	HUGHES	Not Available

tests, and in amplifier design and evaluation. However, device performance is not adequate to provide suitable transmitters for space application. The "near term" performance estimates represent the performance of current laboratory devices which could be brought into production in time for a late 1980's launch. These are device developments which are within the demonstrated capability of current technology and which will provide HPAs competitive with thermionic devices. The "far term" is the projected performance of devices which might become available in the late 1980's for launch in the 1990's. The realization of these devices is obviously dependent on significant improvements in device design and fabrication, and dependent on long-range, technology development support.

TABLE 4.13

CURRENT AND PROJECTED AVAILABILITY OF SOLID-STATE POWER DEVICES

DEVICE	POWER OUTPUT (WATTS)								
	PRESENT			NEAR TERM			FAR TERM		
FREQ (GHz)	20	40	60	20	40	60	20	40	60
GaAs FET	0.5	0.0	0.0	1.0	0.0	0.0	2.0	0.5	0.0
IMPATT	1.0	0.5	0.3	4.0	2.0	1.0	10.0	4.0	2.0

B. Power Combining Technology

Power-combining circuit technology is a necessary adjunct to device development. (Note that chip combining to the limit of current technology is recommended to mitigate the circuit combining complexity.) Nonresonant combiners offer the advantages of broad bandwidth, high inter-module isolation and graceful degradation over resonant combiners. Among the non-resonant combining techniques, the binary combiner represents a "no-risk" approach, i.e., can be easily implemented using available hybrids (microstrip at 7.5 GHz and waveguide at 60 GHz), but incurs the largest size, weight and insertion loss penalty. Spatial combining offers the smallest package and insertion

loss among nonresonant combiners, but requires a compatible antenna design (i.e., phased array or MBA). For applications requiring high power in a single envelope, the N-way combiner has potential advantages over the binary combiner, but N-way combiner technology requires further development. Specifically, the design and implementation of generic combiner techniques and the choice of appropriate transmission lines at EHF require investigation. The resonant cavity combiner, while affording the smallest amplifier package and highest combining efficiency, has had inherent disadvantages of narrow bandwidth and catastrophic failure modes. Efforts directed toward design improvements and failure-mode analyses are required to mitigate these shortcomings.

C. Transmitters

A summary of solid-state power devices and their suitability for various transmitter applications is presented in Fig. 4.16. At 7.5 GHz, GaAs FETs have the necessary gain, power and efficiency to meet most spacecraft power amplifier requirements, and are the recommended device. Although IMPATT diodes provide higher output power, GaAs FETs are the recommended solution whenever they have the requisite performance due to their higher efficiency, relative ease of combining and linear amplification. At 20 GHz, GaAs FETs are currently suitable for lower power levels. However, GaAs FET technology is rapidly advancing, and with continued development effort at 20 GHz, should be a viable candidate for all amplifier applications. At 20 GHz, IMPATT diodes will offer a factor-of-two-to-four higher output power and comparable efficiency and gain to GaAs FETs. Consequently, both GaAs FETs and IMPATTs are viable HPA candidates and warrant continued development. The final device selection will be based on the specific application (e.g., linear versus saturated amplifier), and the relative advances in both device and combiner technology. It is doubtful that power GaAs FETs will offer useful performance at 40 GHz and above in the near term. (Note that small-signal GaAs FETs may be available at 40 GHz in the near term, e.g., Hughes has developed such devices with gain at 38 GHz.) Consequently, IMPATT diodes must be employed in power applications at 40, 45 or 60 GHz. GaAs IMPATTs offer comparable power at higher efficiency than silicon, and are recommended for development.

DCA-7(4.16)

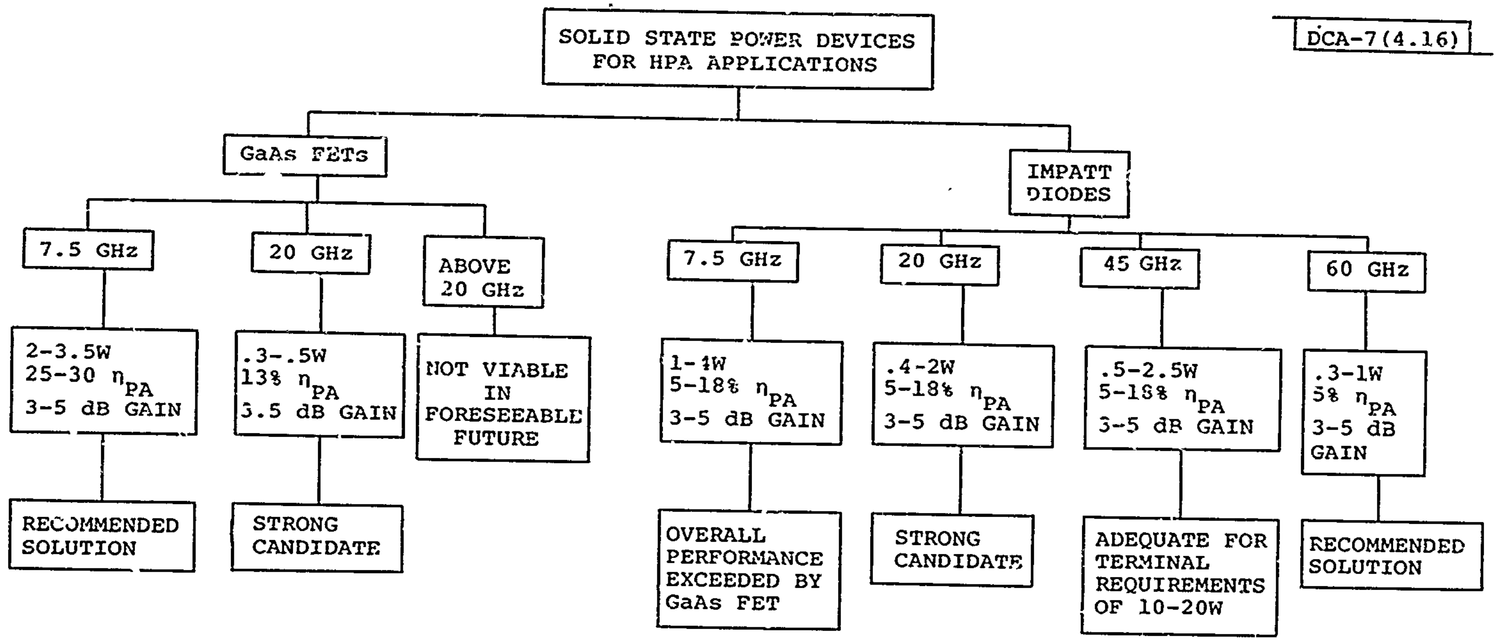

Fig. 4.16. Suitability of current solid-state power devices for EHF amplifiers.

D. Advanced Developments

There are specific device developments that would enhance the performance of SSAs and are within the capability of current technology. The recommended advanced device developments are given in Table 4.14.

TABLE 4.14

RECOMMENDED ADVANCED DEVICE DEVELOPMENT

FREQUENCY (GHz)	DEVICE	GOALS
7.5	GaAs FET	5 W, 30-40% η_{PA}, 5 dB Gain
20	GaAS IMPATT	4 W, 20-25% η_{PA}
	GaAs FET	1 W, 20-25% η_{PA}, 5 dB Gain
45	GaAs IMPATT	2 W, 15% η_{PA}
60	GaAs IMPATT	1 W, 15% η_{PA}

E. Reliability

There is a danger that the excellent reliability demonstrated by solid-state devices at lower freuqencies may lead to a situation of complacency at EHF. Devices at EHF are typically at the limit of current production technology and may operate at higher voltages and temperatures than their lower frequency counterparts. Consequently, extensive reliability and life tests are required. As discussed in Section III, TWT reliability and life test facilities are being implemented at RADC and NRL. Although the cost of these facilities and the test articles greatly exceeds the cost of corresponding solid-state testing, no comparable solid-state effort is being undertaken. A comprehensive solid-state reliability program is required, and should ecompass: extensive screening procedures to eliminate defective devices; testing of the device's operating voltage and temperature margins; large-scale life testing to provide representative statistics; MILSPEC qualification testing for the appropriate application; and MILSPEC qualification and life testing of complete solid-state amplifiers.

V. PROPAGATION EFFECTS

5.1 Background

Rain attenuation is a critical parameter in the design of MILSATCOM systems operating at EHF. For a specified frequency and link availability (as dictated by the unique requirements of the user), the rain attenuation is a significant factor in determining satellite constellations, and terminal size and cost. Consequently, accurate estimates of rain attenuation on a global basis are required and are presented in this section.

It is generally accepted that rain rate data must be collected for a minimum period of 10 years to adequately define the rain rate statistics for a given location. Statistically representative rain attenuation data would then require observations for an equal period of time. As radiometer measurements at EHF suffer from inadequate dynamic range, rain attenuation measurements would require an EHF beacon on a geostationary satellite. At the end of a 10-year period, rain attenuation distribution data would be available only for those specific locations, elevation angles and frequencies for which satellites and instrumented sites were provided. The point being made is obvious, a global rain attenuation prediction model is required. Note that the data collection process is still necessary, not as the basis for assessing the impact of rain attenuation, but rather to evaluate and refine the modeling process.

This section first briefly addresses the attenuation due to particulate scattering other than rain to place it in proper perspective. Next, a refined version of the global attenuation prediction model reported previously[1] is described, and extensive estimates based on this improved model are presented.

5.2 Non-Rain Propagation Effects

The attenuation due to atmospheric absorption, clouds, fog, snow and sleet were addressed in the previous report[1]. This subsection briefly addresses the attenuation at EHF due to sandstorms, and its concomitant impact on satellite communications links. The sandstorms considered are associated with natural

occurrence. (The "dust cloud" associated with nuclear bursts has been extensively modeled by DNA.) There is a paucity of available data regarding the probability of occurrence of sandstorms, the density and distribution of particles within the storm, and, in particular, measured attenuation. The estimates presented herein are based on a theoretical model[11] as described in the following paragraph. These estimates are believed to provide a reasonable upper bound on the attenuation values.

The assumed parameters for the sandstorm model are as follows. As sand grains of diameter > 0.2 mm are typically driven by the wind only to heights < 2 m, this value of diameter is taken to be an upper bound (realistically, only a potential problem on a terrestrial communication path). Dust-like sand particles (diameter, $d < 0.02$ mm*) can rise in dense clouds to a height of 1 Km or more. Dust clouds may reach heights of tens of kilometers and may be transported intercontinental distances, e.g., the outflow of dust from northwestern Africa (the "red" dust) which may be deposited over wide areas of the Mediterranean, Europe and the mid-Atlantic. However, the number density of particles is estimated[12] to decrease from the surface value by an order of magnitude for each ten kilometer increase in height. (There is a concomitant decrease in the median diameter of the dust particles but it is not quantified.) The sand particles in the model are then assumed to be spheres of 0.02- to 0.2-mm diameter. The dielectric constant is assumed to be in the range of 2.5(1-j0.01) to 10(1-j0.01). The dielectric constant of 2.5 is that of dry soil; the loss tangent of 0.01 and the dielectric constant of 10 are probable upper limits for sand particles in a desert environment. For each particle size considered, a uniform distribution is assumed. The number density of sand particles is determined from the standpoint of visibility conditions** (optical attenuation coefficient). Fig. 5.1 presents 45 GHz attenuation as a function of visibility for the above assumed parameters.

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*The particle size distribution typically observed[12] near the surface is proportional to d^{-3}, for 10^{-4}mm $< d < 10^{-2}$mm.

**A threshold of contrast of 0.031 is assumed[13] in the calculation of visual range.

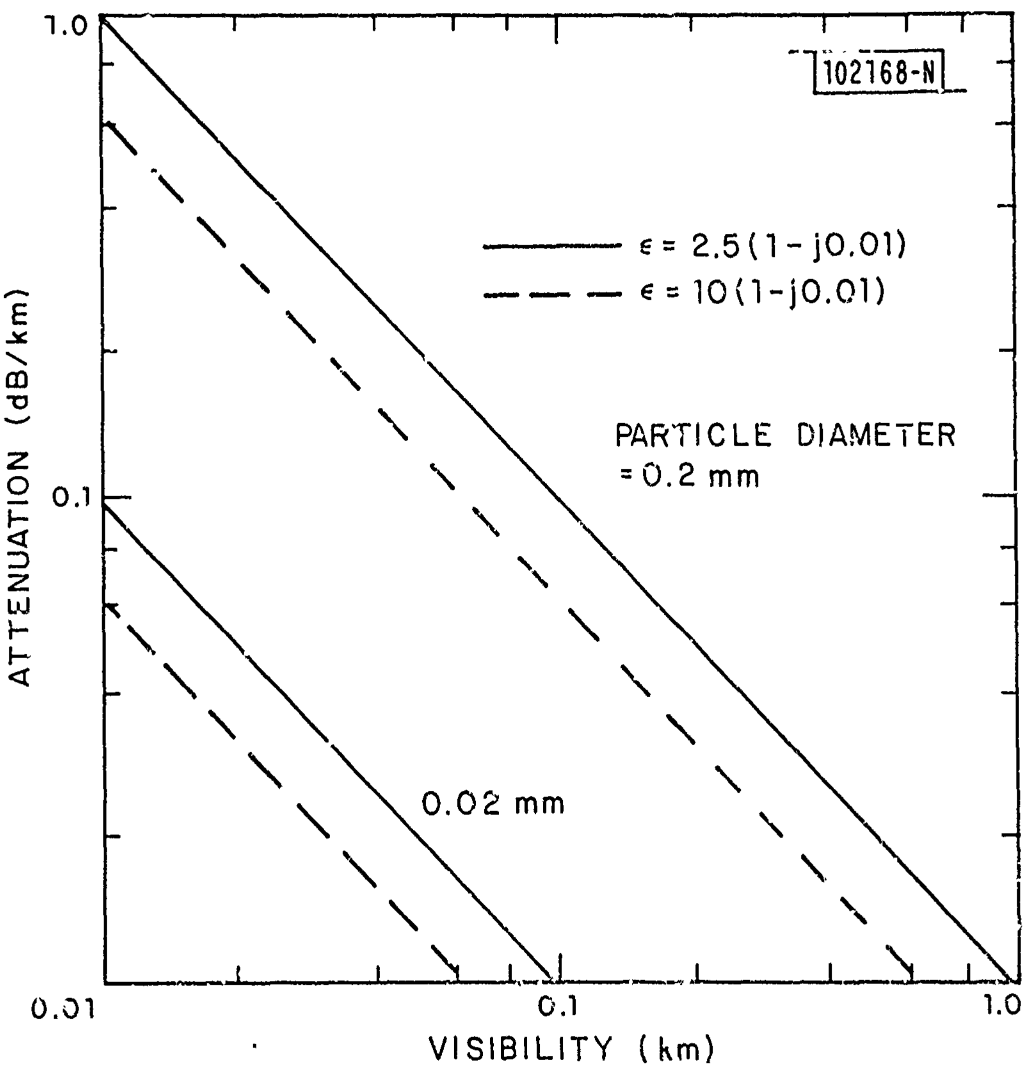

Fig. 5.1. Calculated 45 GHz attenuation as a function of visibility in a uniform sandstorm.

Note that for a given visibility, the attenuation has a linear dependence on particle size. It should be pointed out that the attenuation also has a linear dependence on frequency.

In summary, for 100-ft. visibility in a sandstorm consisting entirely of 0.2-mm diameter particles, the attenuation coefficient at 45 GHz is 0.35 dB/km. For a terminal operating at an elevation angle of 10^{o}, through a sandstorm having a vertical extent (H) of 1 Km, the additional path attenuation incurred would be 2 dB*. To place the attenuation due to sandstorms in proper perspective, Table 5.1 presents zenith attenuation at 45 GHz for various propagation conditions. Note that the attenuation due to clear sky, fair weather clouds, and fog with 100-ft. visibility, each exceed that of the sandstorm. Finally, note that even for light rain (3 mm/h), the rain attenuation far exceeds that due to other phenomena. Obviously, the link margin required to mitigate rain attenuation would be the driving factor in MILSATCOM system design. The remainder of this section addresses rain attenuation models, predictions and duration.

5.3 Global Rain Attenuation Prediction Model

A. Perspective

A global rain attenuation model contains two separate and distinct models: a rain rate climate model which provides a global definition of rain climate regions and corresponding rain rate distributions; and a rain attenuation estimation model which relates attenuation to the frequency of operation, rain rate along the propagation path, and length of the path. As discussed in Section 5.1, there is a paucity of measured data from which such models can be derived. Consequently, the prediction of rain attenuation on a global basis is a statistical process. The constituent parameters of the predictive model which must be based on statistical averages include:

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*A more realistic, but still pessimistic, example might be d=0.02 mm, H=10 Km, and would result in the same attenuation estimate.

TABLE 5.1

ZENITH ATTENUATION AT 45 GHz FOR VARIOUS PROPAGATION CONDITIONS

PROPAGATION CONDITION	ZENITH ATTENUATION (dB)	COMMENTS
Clear Sky	0.6	U.S. Standard Atmosphere: $M=7.5\ g/m^3$ at the surface
Fair Weather Clouds	0.4	Cumulus Clouds: $M=0.2\ g/m^3$, $H=1$ Km
Dense Fog	0.9	100-ft. Visibility: $M=2.3\ g/m^3$, $H=0.2$ Km
Sandstorm	0.35	100-ft. Visibility: Diameter=0.2 mm, H=1 Km
Rain		
3 mm/h (1.0%)	2.0	Rain rate exceeded (%) of the year in temperate climate (Region D)
15 mm/h (0.1%)	14	
50 mm/h (0.01%)	58	

Note 1: M = liquid water content (g/m^3); H = vertical extent of condition.

Note 2: With the exception of rain, attenuation (A) as a function of elevation angle (θ) is given by A = A(Zenith) csc(θ), for $\theta > 10^o$.

1. rain rate versus probability of occurrence, which is a spatial and temporal average of available statistics for given geographic regions.

2. vertical extent of the rain which has a seasonal and rain rate dependence, as well as a latitude dependence.

3. rain rate distribution along the propagation path.

As the predictive models are based on such statistical processes, the resultant attenuation estimates incur large uncertainty bounds. In order to realize the most representative global rain attenuation estimates, it is then necessary to utilize the most accurate predictive models and to refine these models on a continuous basis. This section presents a refined rain rate climate model and an improved rain attenuation estimation model. These models were generated by R. K. Crane[14,15] of Environmental Research and Technology, Inc., and are based on the models proposed in his CCIR submission (CCIR-1978a, Doc P/105-E, 6 June).

B. Rain Rate Climate Model

The rain rate climate model[14] presented in this subsection contains refinements in both the definition of the global rain rate climate regions and in the corresponding rain rate distributions. The refinements in the rain rate climate regions include:

1. Changes in the global regional boundaries based on additional precipitation data.

2. Subdivision of Regions B and D in North America and Western Europe.

These refinements are intended to reduce the inherent uncertainty bounds in the attenuation estimation due to the spatial averaging of rain rate statistics over large geographic areas. Fig. 5.2 presents the new global rain rate climate regions; Figs 5.3, 5.4 and 5.5 present expanded regional definitions for CONUS, Canada and Europe, respectively, and contain the regional subdivisions. Note that the climate regions are defined (within obvious constraints) so that the rain rate distributions for adjacent regions

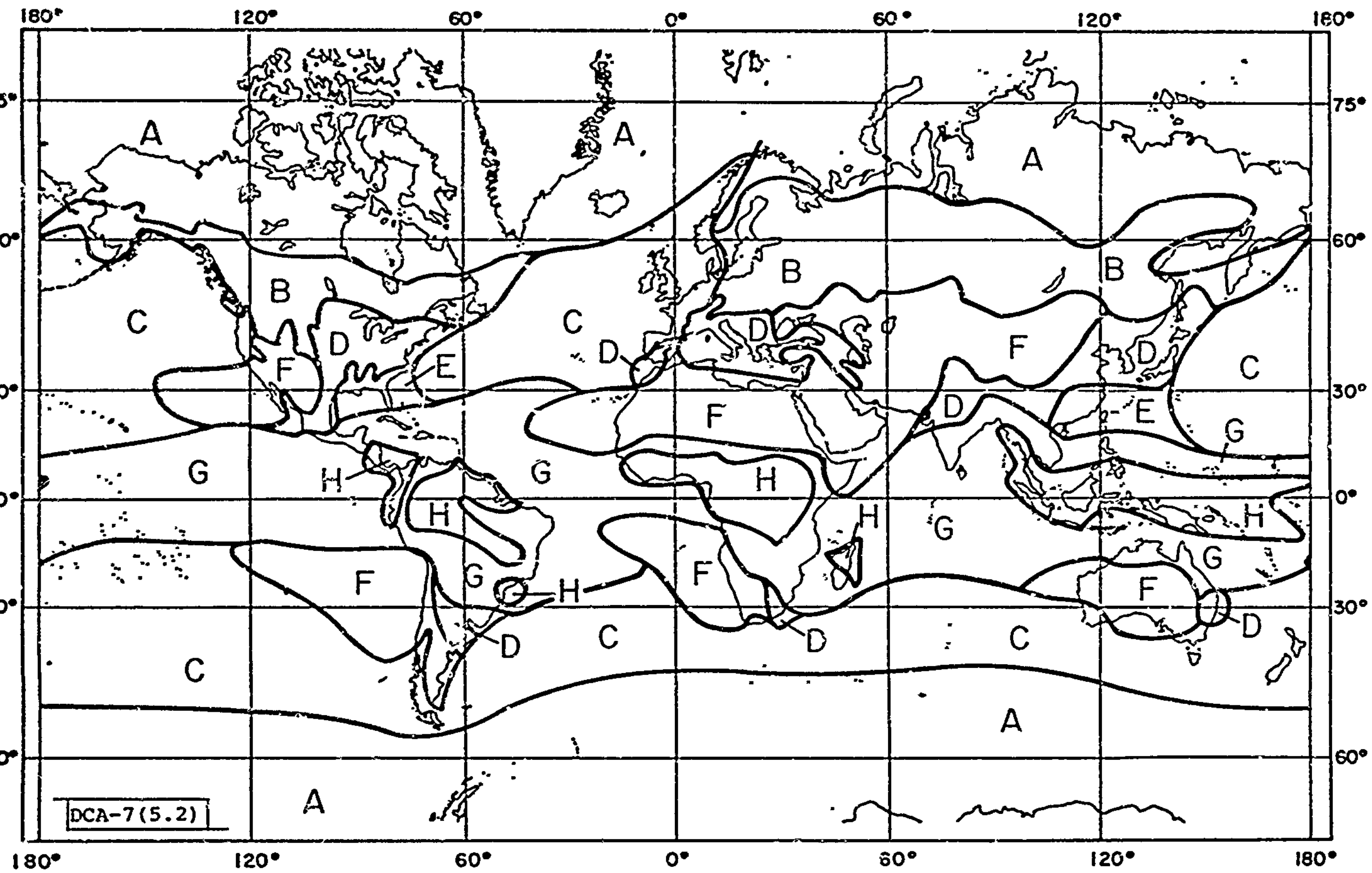

Fig. 5.2. Global rain rate climate regions.

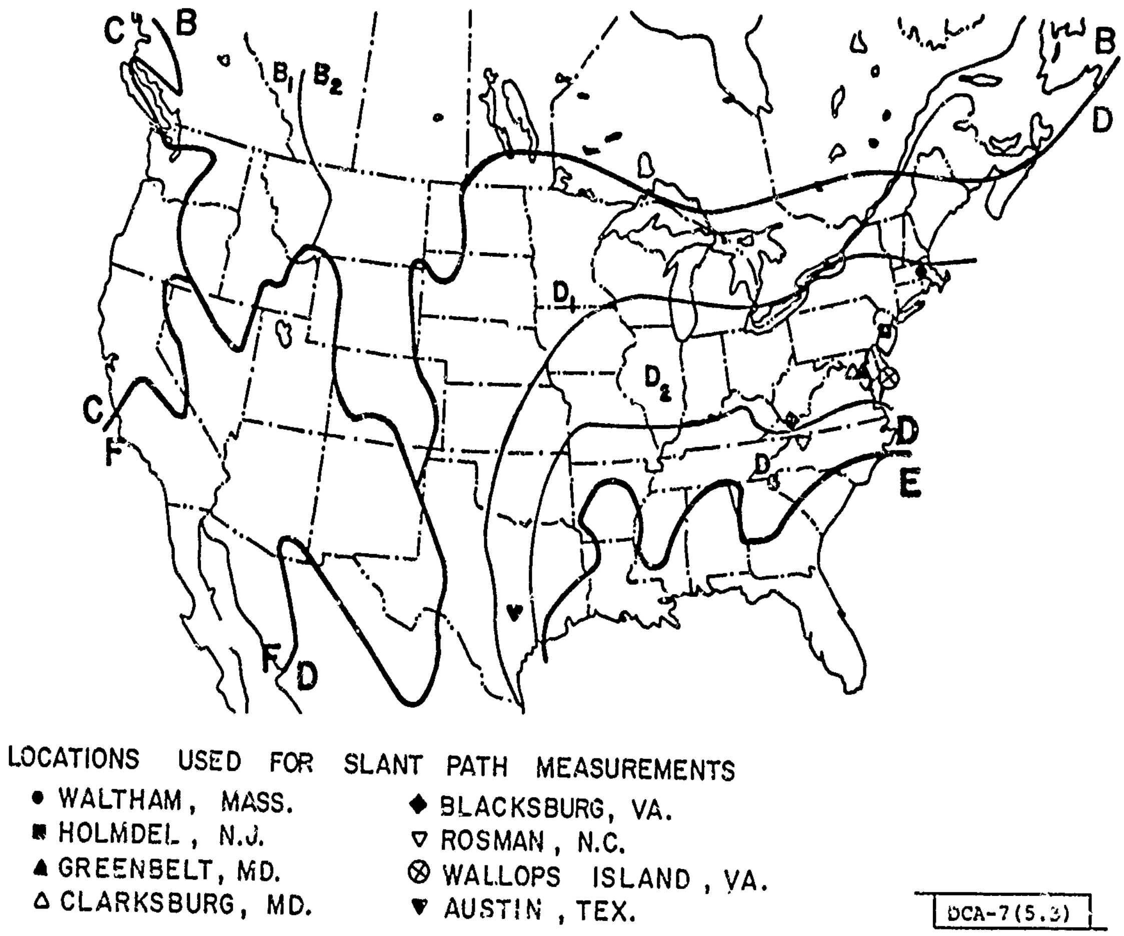

Fig. 5.3. Rain rate climate regions, United States.

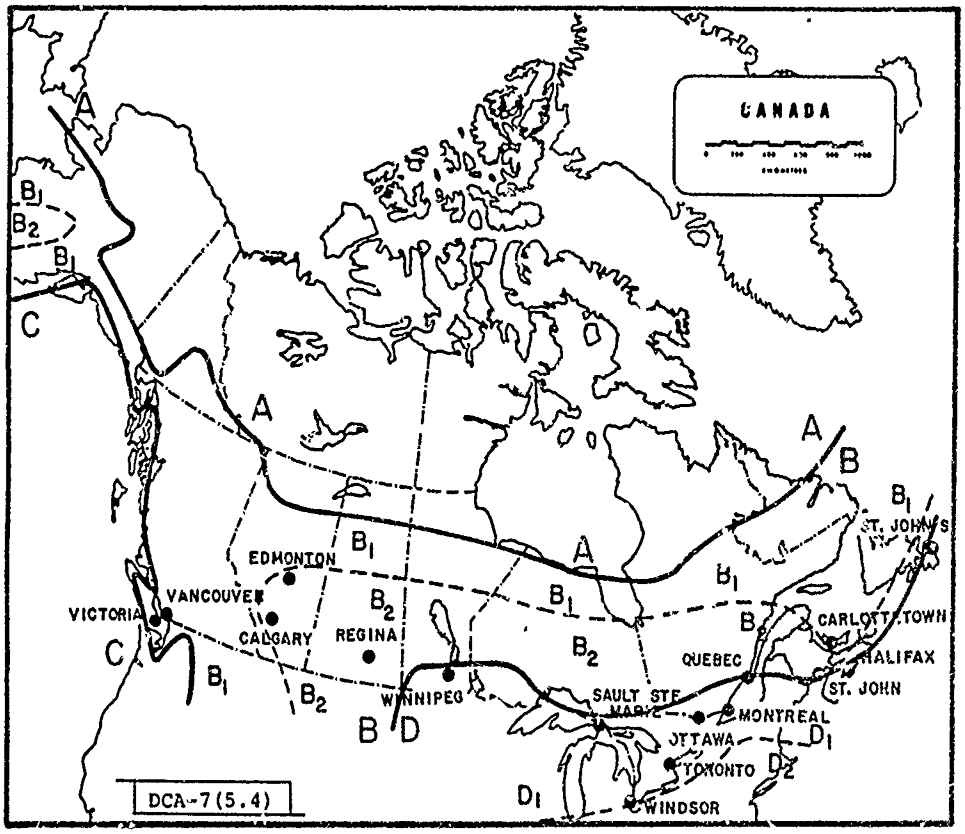

Fig. 5.4. Rain rate climate regions, Canada.

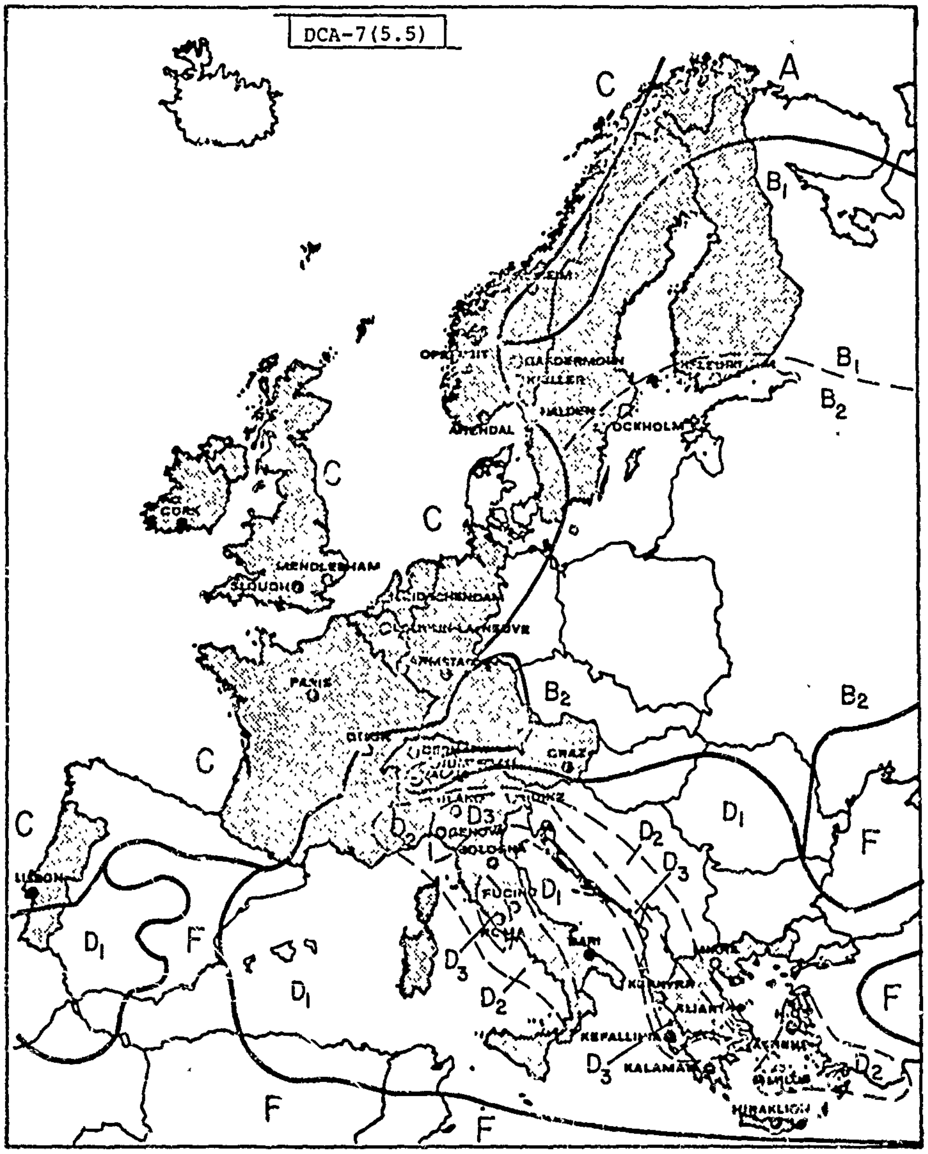

Fig. 5.5. Rain rate climate regions, Europe.

bound the possible spatial and temporal variation of the distribution for the region of interest.

The rain rate distributions have been modified to be consistent with the latest climatological data. These modifications include:

1. New rain rate distribution for Region A which represents only rain (previous data included all precipitation).
2. Extension of the rain rate distribution from 0.0001% to 10% of the year.

In the latter case, the rain rate distribution for each climate region is now consistent with the total annual rain for that region. In addition, the rain rate distributions are extended into the transition region (i.e., cloud cover) between a rain environment and clear sky. The rain rate distribution functions for each climate region are presented in Fig. 5.6; extensive rain rate distribution values are presented in Table 5.2.

C. Rain Attenuation Estimation Model

Given the surface point rain rate statistics of the previous section, a rain attenuation estimation model requires estimates of the specific attenuation (primarily a function of operating frequency and raindrop size distribution), the propagation path length (a function of the freezing layer height and elevation angle), and the rain rate distribution along the path (a function of the point rain rate and length of the path). The estimation of specific attenuation has received considerable attention, and theoretical values are in good agreement with experimental observations. The coefficients in the power law relationship between specific attenuation and freqency for the model are presented in Figs. 5.7 (multiplier, $\alpha(F)$) and 5.8 (exponent $\beta(F)$), and are delineated in Table 5.3. These values were obtained for a Laws and Parsons drop size distribution and a $0^{o}C$ drop temperature.

Models for the estimation of the propagation path length through rain on an earth-satellite path start with the determination of the vertical distance between the height of the earth terminal and the $0^{o}C$ isotherm height (H). (It

TABLE 5.2

RAIN RATE DISTRIBUTION VALUES (MM/H)

PERCENT	RAIN RATE CLIMATE REGIONS											
OF YEAR	A	B1	B	B2	C	D1	D=D2	D3	E	F	G=D3	H
0.0001	69	93	110	126	134	149	173	196	234	118	196	358
0.0002	54	76	93	109	117	130	153	175	213	102	175	325
0.0003	46	67	83	99	107	120	142	163	201	93	163	307
0.0005	38	57	72	87	94	108	128	147	186	81	147	284
0.0007	33	51	65	79	86	99	118	137	176	74	137	269
0.001	28.5	45	58	70	78	90	108	126	165	66	126	253
0.002	21.0	34	44	54	62	72	89	106	144	51	106	221
0.003	17.5	29	37.5	46	52	62	78	95	133	43	95	201
0.005	13.5	22	28.5	35	41	50	65	81	118	34	81	178
0.007	12.0	18.5	23.7	29	35	43	57	72	108	29	72	163
0.01	10.0	15.5	19.5	23.5	28	36	49	63	98	23	63	147
0.02	7.0	11.0	13.5	16.0	18	24	35	48	78	15	48	116
0.03	5.5	8.6	11.1	13.5	14	19	29	40	66	11.5	40	98
0.05	4.0	6.4	8.0	9.5	11	14.5	22	32	52	8.3	32	77
0.07	3.2	5.2	6.5	7.7	8.8	12.0	18	27	43	6.6	27	64
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22	35	5.2	22	52
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21	3.1	14.5	32.5
0.3	1.1	2.2	2.7	3.1	3.7	4.9	7.3	11.2	16	2.2	11.2	24.0
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	7.8	16.0
0.7	0.5	1.2	1.5	1.8	2.2	2.9	3.8	6.1	8.2	1.0	6.1	12.5
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	4.7	9.3
2.0	0.1	0.5	0.7	0.8	1.1	1.2	1.5	1.9	2.9	0.2	1.9	4.7
3.0	0.0	0.3	0.5	0.6	0.9	0.7	0.8	1.0	1.6	0.0	1.0	2.9
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	0.0	1.2
7.0	0.0	0.1	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.4
10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

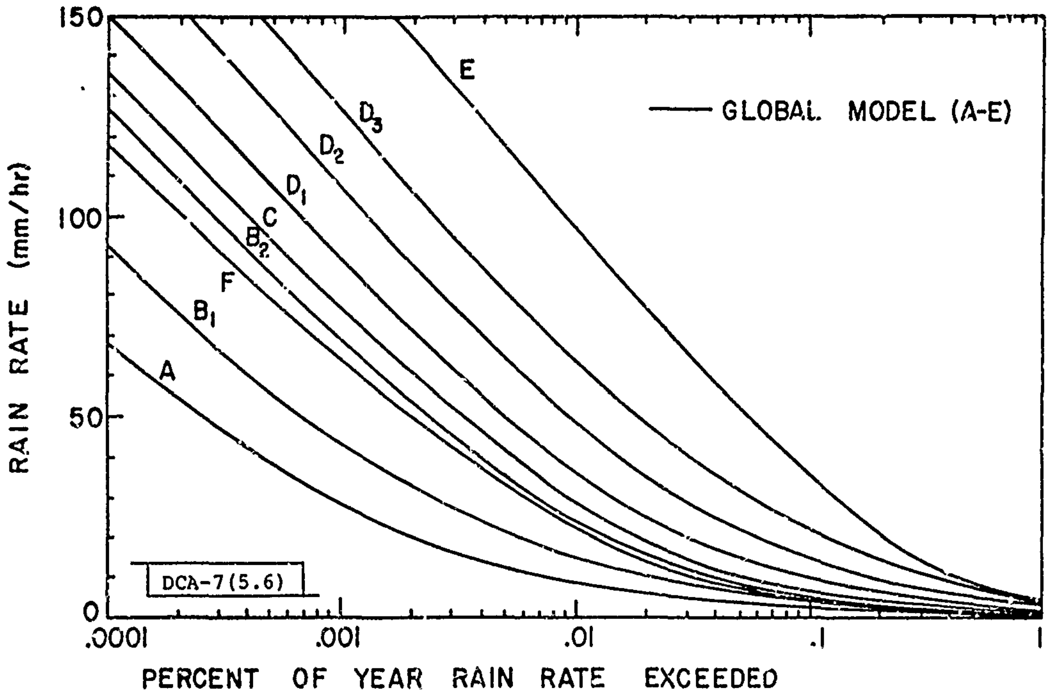

Fig. 5.6. Rain rate distributions.

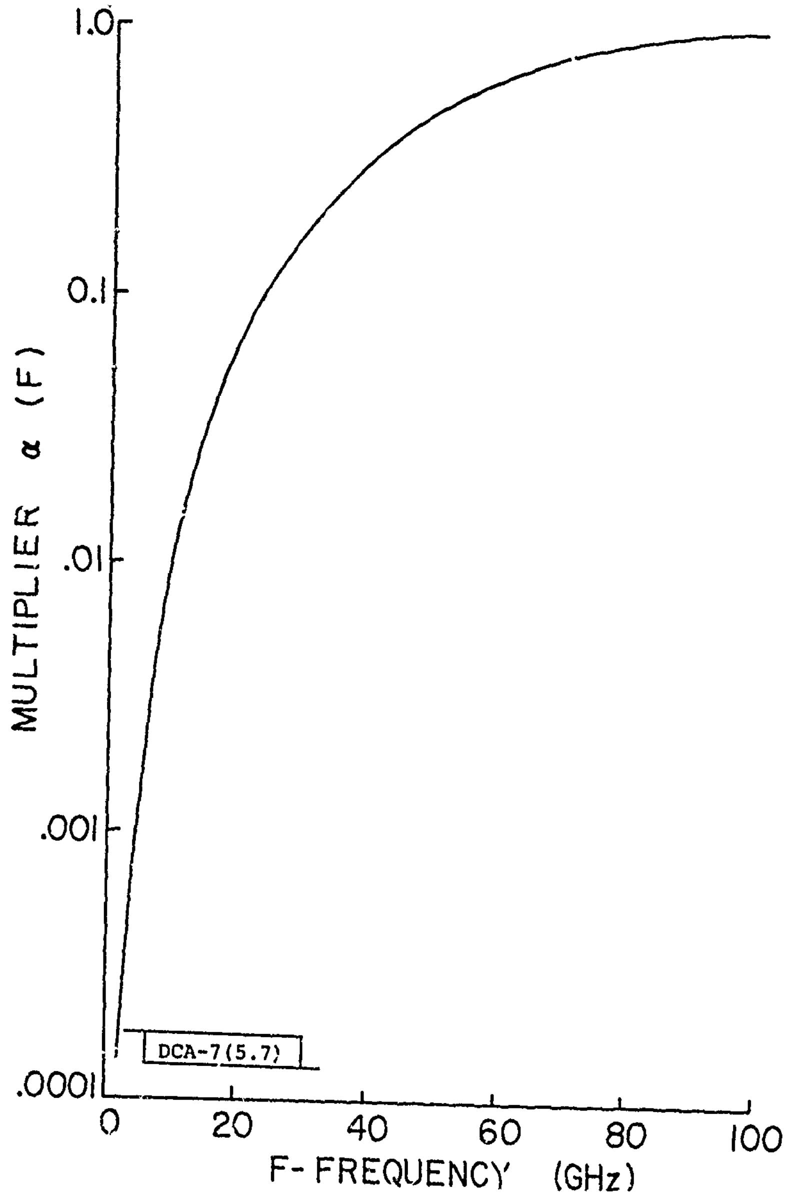

Fig. 5.7. Multiplier in the power law relationship between specific attenuation and frequency.

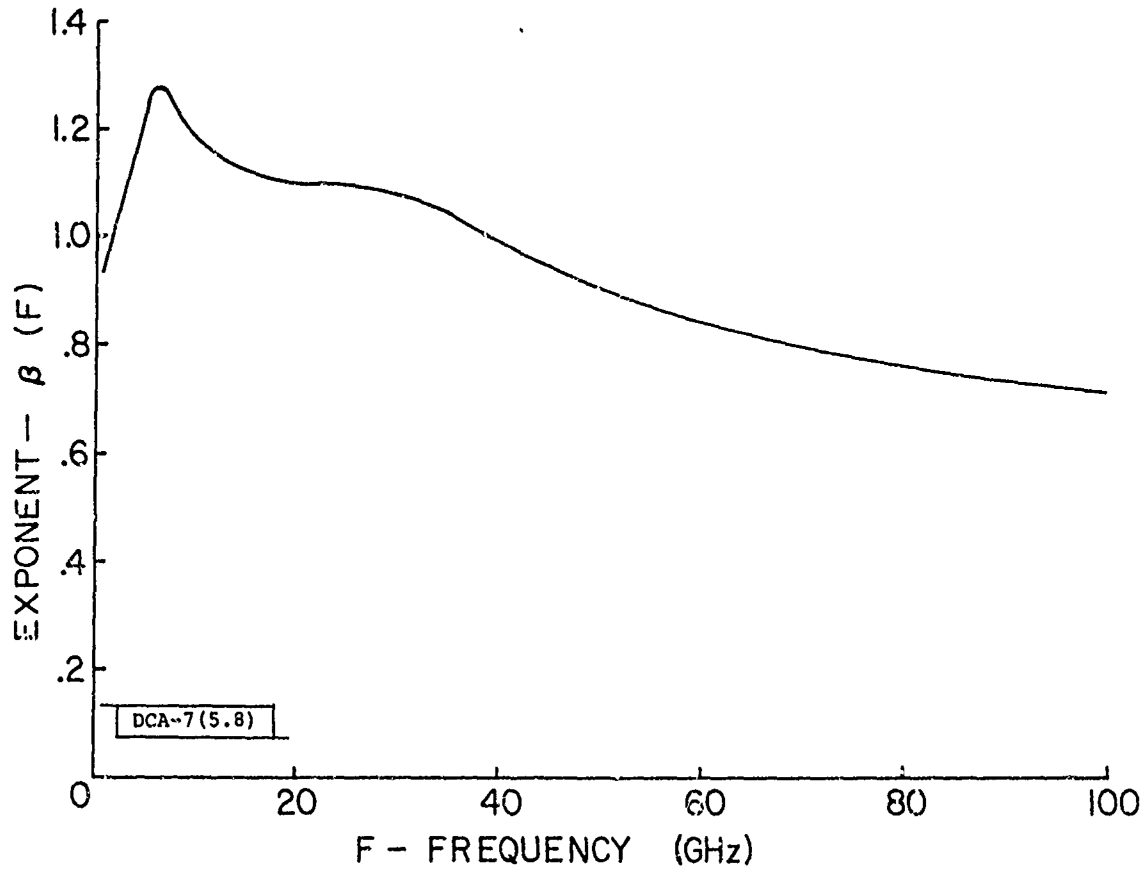

Fig. 5.8. Exponent in the power law relationship between specific attenuation and frequency.

TABLE 5.3

PARAMETERS FOR COMPUTING SPECIFIC ATTENUATION

$a = \alpha R_p^{\beta}$ (dB/Km)

Frequency (GHz)	Multiplier $\alpha(F)$	Exponent $\beta(F)$
1	0.00015	0.95
4	0.00080	1.17
5	0.00138	1.24
6	0.00250	1.28
7.5	0.00482	1.25
10	0.0125	1.18
12.5	0.0228	1.145
15	0.0357	1.12
17.5	0.0524	1.105
20	0.0699	1.10
25	0.113	1.09
30	0.170	1.075
35	0.242	1.04
40	0.325	0.99
50	0.485	0.90
60	0.650	0.84
70	0.780	0.79
80	0.875	0.753
90	0.935	0.730
100	0.965	0.715

is generally assumed that the rain rate is uniform from the surface to the $0^{o}C$ isotherm height where rapid conversion from water to ice occurs.) To determine the propagation path length (L) through the rain, models assume a cosecant path length dependence, i.e., $L = H \csc \theta$, $\theta > 10^{o}$. The rain attenuation estimate for a given rain rate, frequency, and elevation angle is then directly proportional to the estimated $0^{o}C$ isotherm height. In the previously reported model[1], the height of the $0^{o}C$ isotherm is presented as a function of latitude, and is seasonally (for all weather conditions) and zonally averaged (averaged in longitude for a constant latitude). However, the height of the $0^{o}C$ isotherm displays a marked seasonal dependence which, coupled with the seasonal variation in the occurrence of rain, indicates that the $0^{o}C$ height to be used for the prediction of attenuation should have both a latitude and a probability of occurrence dependence. The dependence of the $0^{o}C$ height on general rain conditions was established[14] using upper air sounding data, surface maps to establish the occurrence of precipitation, and excessive precipitation data to establish the correlation between $0^{o}C$ height and the occurrence of excessive precipitation events. As a model for the prediction of attenuation, the average height of the $0^{o}C$ isotherm for days with rain was taken to correspond to the height to be expected 1 percent of the year. The highest height observed with rain was taken to correspond to the value to be expected 0.001 percent of the year. The resultant model of the $0^{o}C$ isotherm height is presented in Fig. 5.9.

The correspondence between the $0^{o}C$ isotherm height and the excessive precipitation events shows a tendency toward a linear relationship between rain rate (R_p) and H for high values of R_p. Since, at high rain rates, the rain rate distribution function displays a nearly linear relationship between R_p and log P (where P is the probability of occurrence), the interpolation model used for the estimation of H for P between 0.001 and 1 percent is assumed to have the form

$$H = a + b \log P. \qquad (5.1)$$

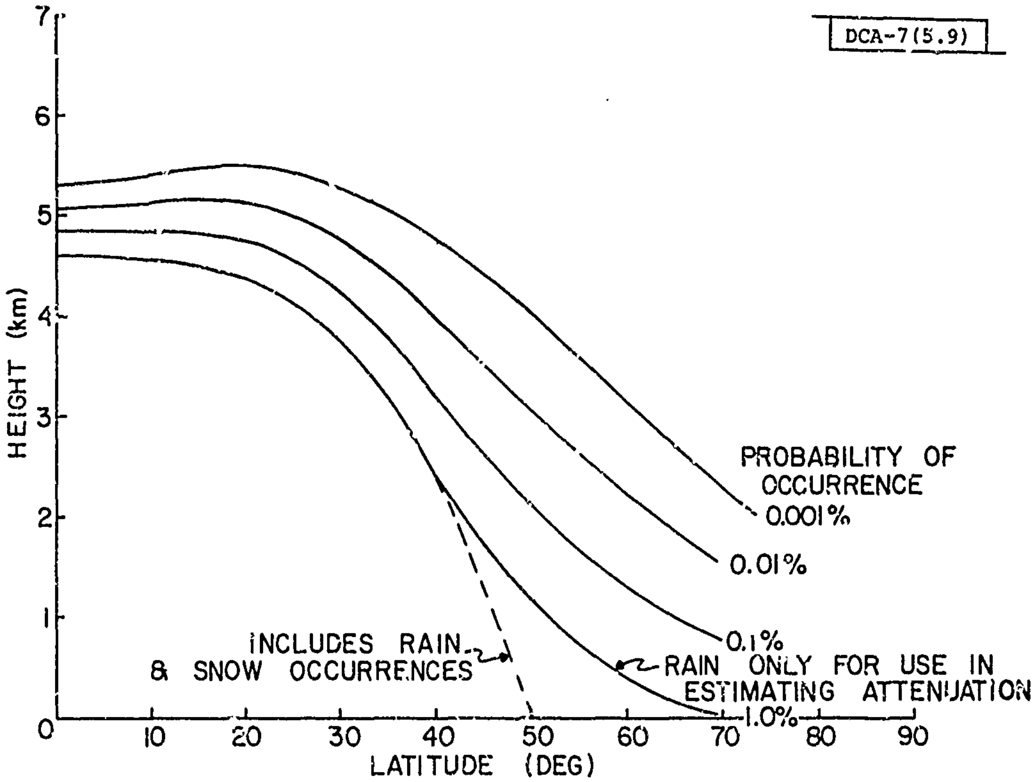

Fig. 5.9. 0°C isotherm height for use in estimating the depth of the attenuating region on a slant path.

This relationship was used to provide the intermediate values displayed in Fig. 5.9, and is to be used to provide other values of interest. This refinement in the model of the $0^{o}C$ isotherm height will provide better estimates of the rain attenuation as it more accurately represents the dependence of the $0^{o}C$ height on the meteorological conditions (i.e., rain rate and season).

The attenuation prediction model also includes a refinement in the estimation of the path averaged rain rate or effective path average factor. The problem lies in the fact that the path average rain rate exceeded for a specified percentage of time may differ significantly from the point rain rate exceeded for the same percentage of time. This inhomogeneous rain rate distribution along the path is evident in rain attenuation observations and has led to the concept of an effective path length. The solution applied in other models has been to empirically derive an effective path length factor based on a set of observed attenuation values. The previously reported model[1] addressed the spatial distribution of the rain rate by using observations from rain gauge networks to provide a basis for a point-to-path average rain rate model. A power law relationship was empirically established from the rain gauge data to provide a model of the effective path average factor (r) which may be expressed as

$$r = \gamma(D)R_p^{-\delta(D)} \tag{5.2}$$

where R_p is the point rainfall rate exceeded p percent of the time, and D is the surface projection of the propagation path. This path average model produces the desired relationship between the rain rate at a point and the rain rate averaged over the path. However, the specific attenuation is a nonlinear function of point rain rate, and, hence, the model is not adequate for the estimation of attenuation. A statistical model of the profile of instantaneous rain rate along the path is required which then can be integrated to provide the desired attenuation value. The new model uses exponential functions to fit the spatial derivative of the path average rain rate model (Eq. 5.2). An adequate model results from using two exponential

functions to span the 0 to 22.5* Km distance range (D), one from 0 to d Km, the other from d to 22.5 Km. This piece-wise exponential function is integrated to provide estimates of the attenuation (or path averaged rain rate) along the path. The resultant model is given by:

$$A(R_p,D) = \alpha R_p^{\beta} \left[\frac{e^{\mu\beta d}-1}{\mu\beta} - \frac{b^{\beta}e^{c\beta d}}{c\beta} + \frac{b^{\beta}e^{c\beta D}}{c\beta}\right]; \qquad d < D < 22.5 \text{ Km}$$

$$\tag{5.3}$$

$$A(R_p,D) = \alpha R_p^{\beta} \left[\frac{e^{\mu\beta D}-1}{\mu\beta}\right]; \qquad 0 < D < d$$

where αR_p^{β} = specific attenuation in dB/Km and the remaining coefficients are the empirical constants of the piecewise exponential model,

$$\mu = \frac{\ln(be^{cd})}{d} \tag{5.4}$$

$$b = 2.3\ R_p^{-0.17} \tag{5.5}$$

$$c = 0.026-0.03\ \ln R_p \tag{5.6}$$

$$d = 3.8-0.6\ \ln R_p \tag{5.7}$$

Note that for paths, D, longer than 22.5 Km, the calculation is made for a 22.5-km path, but the R_p value to be used for the 22.5-km path calculation is obtained from the rain rate distribution function at the probability of occurrence, P',

$$P' = P(22.5/D), \tag{5.8}$$

where P is the probability of occurrence of interest.

---

*It is assumed that the occurrence of rain with rates in excess of 1 mm/h are independent over distances larger than 22.5 Km.

The complete model for the estimation of attenuation on an earth-satellite path starts with the determination of the vertical distance between the height of the earth terminal and the $0^{o}C$ isotherm height ($H-H_o$, where H_o is the terminal height) for the percentage of the year (or R_p) of interest. The surface projection of the path between the surface and the $0^{o}C$ isotherm is used to calculate D:

$$D = (H-H_o)/\tan\theta \quad ; \quad \theta > 10^{o} \tag{5.9}$$

$$D = E\psi, \quad \psi \text{ in radians} \quad ; \quad \theta < 10^{o} \tag{5.10}$$

where

$$\psi = \sin^{-1}\left[\frac{\cos\theta}{(H+E)}\left(\{(H_o+E)^2\sin^2\theta+2E(H-H_o)+H^2-H_o^2\}^{1/2}-(H_o+E)\sin\theta\right)\right] \tag{5.11}$$

E = effective earth's radius (8500 km)

and

θ = elevation angle

The surface-projected attenuation is calculated from Eqn. 5.3, and, finally, the value for the slant path attenuation, A_s, is estimated using the constancy of specific attenuation below H by

$$A_s = \frac{L\ A(R_p D)}{D} \tag{5.12}$$

where $L = D/\cos\theta \quad ; \quad \theta > 10^{o}$ (5.13)

$$L = [(E+H_o)^2 + (E+H)^2 - 2(E+H_o)(E+H)\cos\psi]^{1/2}, \qquad \theta < 10^\circ \tag{5.14}$$

Note that for elevation angles less than a few degrees, tropospheric induced scintillation effects may be significant. Models of these effects are available[15] should such low elevation angles be of interest.

D. Comparison With Experiment

Recent observations using the CTS, COMSTAR and ATS-6 satellite beacons have been used to evaluate the rain attenuation prediction model at a number of frequencies and locations. Comparisons[14] between observations and model calculations show good agreement between measurement and model for percentages of the year less than 0.1; on average the observations deviate from their model predictions by less than 8 percent. The rms deviation of all the measurements about the models is 26%, in agreement with the 29% rms uncertainty expected for a 1-year set of observations (i.e., expected year-to-year variability in the observed values). This temporal limitation on available satellite data is an inherent problem in the verification of rain attenuation models and the major shortcoming in the development of such models from observations of rain attenuation.

E. Global Rain Attenuation Estimates

The refined global rain attenuation estimation model may be applied as follows:

1. Determine rain rate distribution, R_p:

   1a. Locate earth terminal on map (Figs. 5.2, 5.3, 5.4 or 5.5) and determine rain climate region (A-H) and latitude (for a climate region determine a representative latitude).

   1b. Obtain rain rate distribution from Table 5.2 (or Fig. 5.6).

2. Establish surface projected path length, D:

2a. Calculate the distance D from

$$D = (H_p - H_o)/\tan\theta \quad ; \quad \theta > 10^\circ \tag{5.15}$$

$$D = E\psi, \quad \text{see Eq. 5.10} \quad ; \quad \theta < 10^\circ \tag{5.16}$$

where

θ = elevation angle

H_o = earth terminal height

H_p = $0^\circ C$ isotherm height obtained by interpolation of Fig. 5.9 for the percentage of time, P, of interest and for the latitude of the terminal

2b. If $D > 22.5$ Km, use $D_o = 22.5$ Km and a new probability of occurrence P',

$$P' = P(22.5/D) \tag{5.17}$$

to obtain the point rain rate for subsequent calculations.

3. Determine α and β for the frequency of interest from Table 5.3 (or Figs. 5.7 and 5.8).

4. Calculate the surface projected attenuation value, A, from the R_p and D (or $R_{p'}$ and D_o) where R_p is the rain rate obtained from the rain rate distribution for the probability of occurrence of interest, P:

$$A(R_p, D) = \alpha R_p^{\ \beta} \left[\frac{e^{u\beta d} - 1}{\mu\beta} - \frac{b^\beta e^{c\beta d}}{c\beta} + \frac{b^\beta e^{c\beta D}}{c\beta} \right] \quad ; \quad d < D < D_o \tag{5.18}$$

$$A(R_p,D) = \alpha R_p \frac{\beta\, e^{\mu\beta D}-1}{\mu\beta} \quad ; \quad 0 < D < d \tag{5.19}$$

$$A(R_p,D) = (H_p-H_o)\alpha R_p^{\beta} \quad ; \quad D = 0\ (\theta = 90^o) \tag{5.20}$$

5. Calculate the slant path attenuation value, A_s:

$$A_s = \frac{L\ A(R_p,D)}{D} = \frac{A(R_p,D)}{\cos\theta} \quad ; \quad \theta > 10^o \tag{5.21}$$

$$A_s = \text{see Eq. 5.14 for L} \quad ; \quad \theta < 10^o \tag{5.22}$$

A computer program of the model is available in FORTRAN IV. To eliminate the need for tedious interpolation, this program contains closed form expressions for the constituent parameters of the model, i.e., atmospheric attenuation, point rain rate distributions, coefficients of specific attenuation, and the 0^oC isotherm height. Consequently, the user need only input the frequencies, elevation angles, probabilities of occurrence and locations of interest.

Global estimates of rain attenuation have been made as a function of climate region, elevation angle, frequency and path availability. The rain rate probability of occurrence has been translated in path availability, i.e., percentage of time when the rainfall rate and attenuation are less than the value presented. Thus the data shows the estimated uplink or downlink margin required to realize a specified percentage path availability. Note that the attenuation estimates being presented include oxygen and water vapor absorption (Table 5.1) in addition to rain attenuation. Table 5.4 presents a summary of path availability for the eight climate regions and the frequencies of interest for a range of path margins. Appendix A presents detailed tabulations of total attenuation in the eight climate regions for path availabilities of 90% to 99.99%, elevation angles of 10^o, 20^o, 30^o, 45^o, 60^o and 90^o, and frequencies of 7, 20, 30, 40, 45 and 50 GHz.

TABLE 5.4

PATH AVAILABILITY ESTIMATES (20° ELEVATION ANGLE)

MARGIN+ (dB)	FREQ (GHz)	CLIMATE REGION							
		A	B	C	D	E	F	G	H
5	20	99.99	99.95	99.85	99.60	98.0	99.80	98.0	96.0
	30	99.97	99.90	99.70	99.10	96.5	99.50	96.7	94.0
	45	99.93	99.75	99.10	97.5	94.0	98.2	95.6	91.0
10	20	*	99.98	99.96	99.88	99.30	99.44	99.30	98.4
	30	99.99	99.94	99.86	99.57	98.0	99.78	98.0	96.0
	45	99.97	99.85	99.70	98.8	96.0	99.30	96.5	93.0
15	20	*	99.99	99.98	99.93	99.60	99.97	99.70	99.20
	30	*	99.96	99.93	99.80	98.7	99.90	98.6	97.4
	45	99.98	99.91	99.80	99.45	97.3	99.65	97.3	94.8
20	20	*	*	99.99	99.96	99.78	99.98	99.82	99.50
	30	*	99.97	99.96	99.85	99.20	99.93	99.15	98.2
	45	99.99	99.94	99.86	99.60	98.0	99.78	97.9	96.0
25	20	*	*	*	99.97	99.83	99.99	99.89	99.68
	30	*	99.98	99.97	99.90	99.43	99.95	99.45	98.6
	45	*	99.96	99.92	99.75	98.4	99.85	98.3	96.8
30	20	*	*	*	99.98	99.87	*	99.93	99.76
	30	*	99.99	99.98	99.92	99.53	99.97	99.62	99.05
	45	*	99.97	99.95	99.82	98.8	99.91	98.6	97.4

+Allocated for atmospheric absorption plus rain attenuation

*Path Availability > 99.99%

A general computer program has been written to compute system availability and plot the results as contours on a Mercator grid map. This System Availability Predictor Model (SAPM) operates on the following user supplied input parameters: frequency (GHz), subsatellite point, satellite altitude, link margin (dB), terminal availability, and satellite availability. All aspects of the Crane climate region and attenuation model are included in the SAPM code. Hence, the link availability which is computed on a matrix basis of points spaced by 2.5^o in both latitude and longitude, incorporates all the important variable dependencies (frequency, elevation angle, climate region and season). Slant range differential loss (dB) measured relative to the subsatellite point and oxygen and water vapor absorption losses are also included. The SAPM program, background geometry and climate regions are described in Reference 16 along with 54 computed plots of availability contours for three frequencies (20, 30, and 45 GHz), three margin levels (6, 12, and 18 dB), and 6 equally spaced geostationary subsatellite points. A typical availability contour plot from Reference 16 is presented in Fig. 5.10. Reference 17 incorporates the antenna pattern factor for a multi-beam array onboard the spacecraft into the margin equation used to find the availability contours. These models utilize the original Crane model, and as such, represent upper bounds on the alter-estimates as discussed in the following subsection.

5.4 Summary

Among the various propagation phenomena which would introduce path attenuation in EHF MILSATCOM systems, rain is obviously the dominant factor. The subsequent estimation of the rain attenuation impacts the system design, e.g., satellite constellations and terminal size, and hence the cost and complexity. The system designers must recognize the statistical basis of rain attenuation models and their inherent uncertainty bounds. Accepting these limitations, it is necessary to utilize the most accurate predictive models and to refine these models on a continuous basis. The model presented in this section is an example of such a refinement in the predictive process.

DCA-7(5.10)

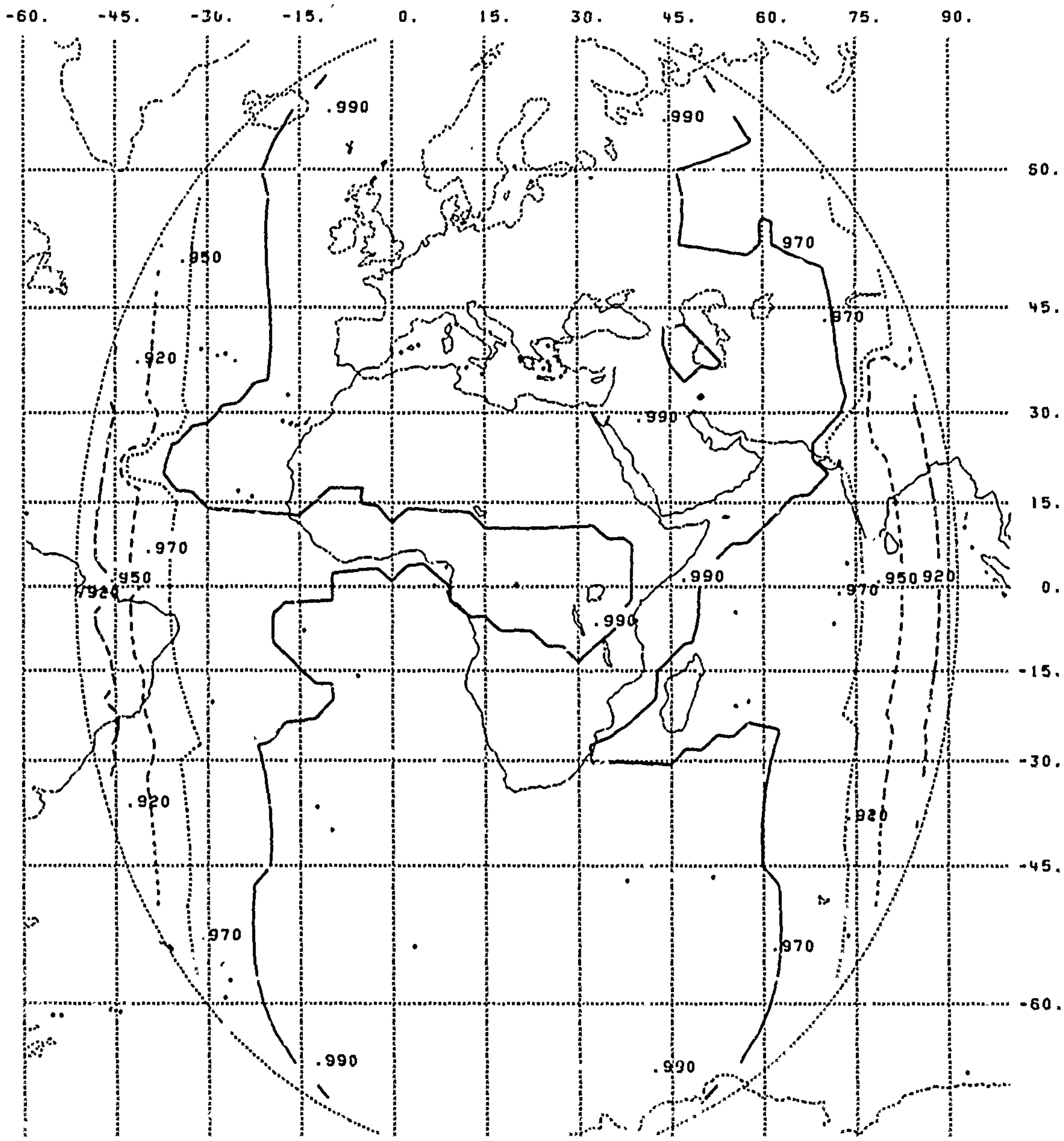

Fig. 5.10. Path availability contours at 45 GHz for a 12 dB path margin and geosynchronous satellite subpoint of 20°E.

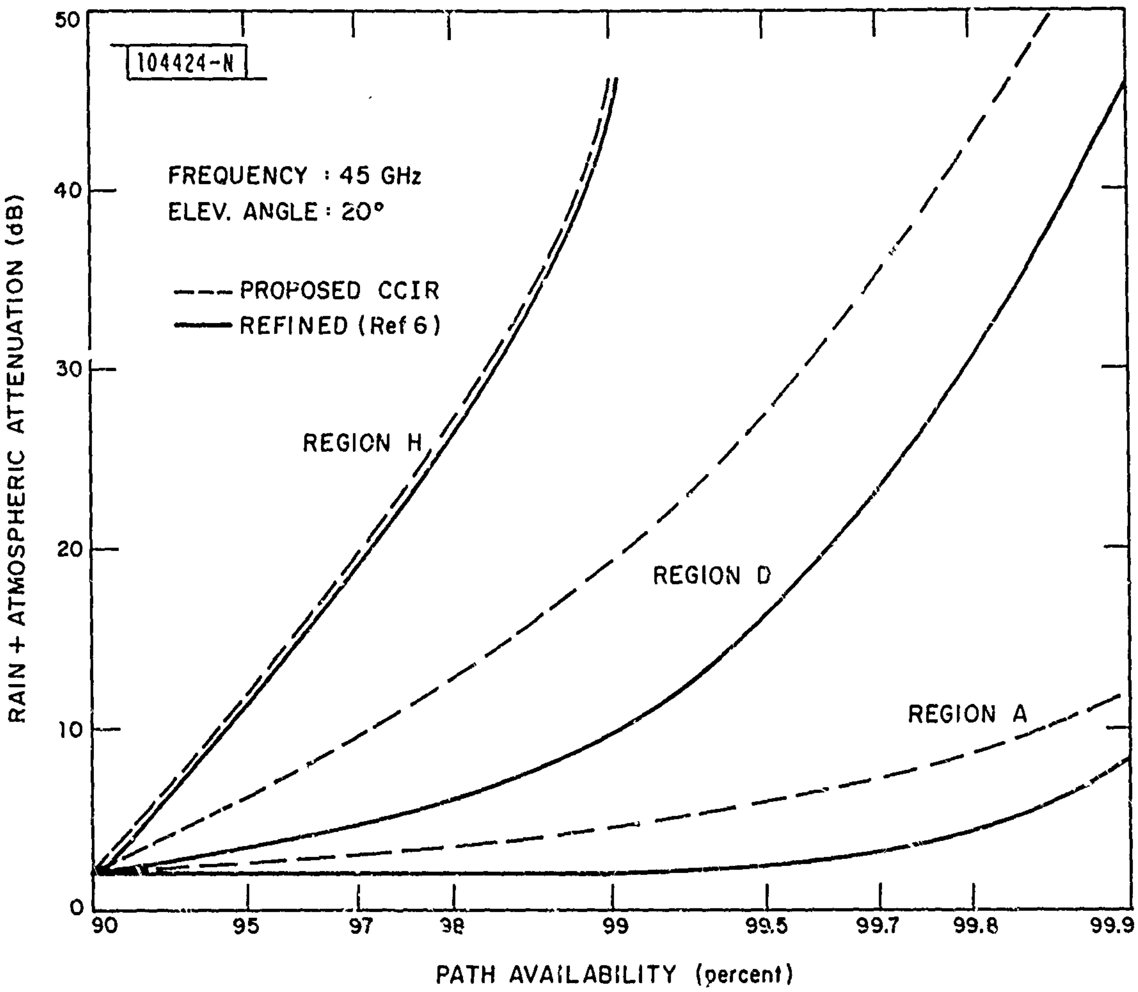

Fig. 5.11. Comparison of estimated rain attenuation vs path availability for two predicitive models.

The main revision in the model presented is the dependence of the 0^{o} isotherm height on the probability of occurrence of rain, which integrates into the model the seasonal variation of both melting layer height and occurrence of rain. Fig. 5.11 presents a comparison of the refined model[6] and the original model (CCIR-1978a). Note that in the tropical region (H), the attenuation estimates are essentially identical, as the seasonal variation in melting layer height is negligible. In the polar region (A), the attenuation predictions of the refined model are consistently lower, but the attenuation estimates for either model are not significant due to the low rain rates. The major difference is in the temperature region (D) where the revised model predicts attenuation which is significantly lower for all path availabilities of interest. It is recommended that this revised model be used for rain attenuation estimates.

VI. TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

6.1 Overview

The orderly transition of MILSATCOM users to EHF will obviously require the timely availability of the necessary technology. Although a technology base exists at EHF, commercially available devices, components, and test equipment are essentially nonexistent, as is the industrial base from which they would stem. The DCA/MSO, in their FMD and TDPP, has elucidated the need for rigorous R&D programs with long-term planning, funding and coordination within the DoD community. In addition to advancing the state of EHF technology, these development efforts must minimize the associated cost and risk in a manner that is time-phased with both space and ground segment deployment. The following is a summary of those factors relevant to the implementation of the required R&D programs and ultimate realization of the necessary technology:

1. A technology base exists from which the technology necessary to support future EHF MILSATCOMs can evolve. However, there is not currently available an adequate commercial or production base at EHF to provide the necessary support. R&D programs in all the major component and subsystem areas are required.

2. In the authors' opinion, commercial interest, adequate to support R&D in the EHF bands, will not materialize in the next decade. Consequently, the DoD must be the primary source of funding* for EHF technology development.

3. The planned evolution of MILSATCOMs to EHF over the next decade affords opportunities for the development of improved system designs and efficient, reliable, cost-effective technology. The implementation of on-board signal processing, and multiple-beam, adaptive-nulling and time-hopped-beam antennas offers the potential for reducing terminal size,

*The 30/20 GHz Satellite Program at NASA/LRC, will lead to EHF hardware development. Coordination between DoD, NASA and other Government agencies is indicated.

complexity and cost. In the component area, solid state devices may provide higher-reliability, lower-cost replacements for current thermionic devices.

4. A concerted, long range EHF technology development program within the DoD is required to exploit the potential advantages of EHF MILSATCOMs. Such a program plan should include among its objectives the delineation, coordination and continuation of the necessary technology development efforts to insure the timely availability of the technology necessary to support future EHF MILSATCOM systems.

6.2 TWT Power Amplifiers

The design theory and lower-frequency technology of TWTAs is relatively mature. However, the TWTA represents the most significant area of hardware development at EHF. For the ground segment, the issues of producibility and cost must be addressed; for the space segment, the problems of producibility and reliability must be resolved. The following recommendations for space and ground segment TWTs encompass three areas of development: 1. Development of TWTs with the requisite performance capabilities; 2. Technology improvement and production technology developments; 3. Qualification, environmental and life testing. In the areas of technology improvement and production technology development, numerous parallel efforts are recommended. The author is aware of the limited funding available within individual SPO's. However, these developments will not cost less if extended, and, more importantly, the selection of the appropriate technology must be made in the near term to support the requisite tube developments, testing and integration. The need for coordinated development efforts within the DoD and other government agencies is evident.

A. Ground Segment

For the ground segment, present coupled-cavity TWT technology is adequate to support currently proposed EHF MILSATCOM requirements. However, the attendant problems of low producibility and high cost must be addressed by production technology efforts directed toward the coupled-cavity circuit, and by the development and evaluation of alternate slow-wave circuits.

a. Potential TWT capabilities based on present technology are summarized in Table 6.1. The power levels are presented in the table as a function of the TWT characteristics which impact their terminal compatibility. Note that these power levels represent the current limits.

b. Recommendations for TWT technology improvement and production development are as follows:

1. Fabricate and test coupled-cavity TWT using "diamond-turned" parts to determine improvement in assembly and test labor, and in tube performance.

2. Expedite development and evaluation of ferruleless coupled-cavity TWT.

3. Develop alternative slow-wave circuits (e.g., HIGHTRON, folded waveguide and quad-comb circuits) to proof-of-concept stage for cost and performance comparison with coupled-cavity technology.

c. Subsequent to the selection of the appropriate TWT technology, the following test program is recommended:

1. Procurement of multiple tubes.

2. MILSPEC qualification testing to appropriate user terminal requirements.

3. Life testing under appropriate environmental conditions.

4. Integration with prototype terminals for evaluation.

B. Space Segment

TWTs have played the dominant role in satellite HPAs. The TWT technology employed, e.g., helical slow-wave circuts and oxide cathodes, is relatively mature and has been successfully exploited at C-Band. However, at X-Band, the problems of producibility and reliability continue to be a concern. As EHF TWTs may require new technology and will certainly not be simpler than X-band TWTs, the current problems of producibility and reliability are critical issues regarding EHF TWT development. Consequently, the recommendations emphasize TWTA technology improvement programs.

a. As regards potential TWT capabilities, 15 and 22-W, 20 GHz TWTs have been developed (Thomson-CSF and AEG-Telefunken, respectively). The

TABLE 6.1

CURRENT TWT CAPABILITIES: GROUND SEGMENT

POWER (WATTS)		SLOW-WAVE CIRCUIT	FOCUSING	COOLING
30 GHz	45 GHz			
50-100	25-50	Helix	PPM	Air*
500	250	Coupled-Cavity	PPM	Air*
1K	500	Coupled-Cavity	PPM	Liquid**
3K	1.5K	Coupled-Cavity	Solenoid***	Liquid

*Airborne and ground mobile terminals

**Shipboard and fixed terminals

***Fixed terminals

planned SD/YKX development of a 20-W, 20 GHz TWT should be encouraged and supported. The basic technology appears capable of supporting a 40-W TWT at 20 GHz, should the requirement arise. At 40 GHz, the 10-W TWT development (RADC/OCTP) is not being used for space application due to the lack of stated requirement. At 60 GHz, TWT feasibility is questionable based on current technology. Current and projected capabilities are summarized in Table 6.2.

b. The following is a list of potential aspects of the TWTA improvement programs derived from discussions with tube manufacturers, sponsors and users.

1. Funding

   Substantial, long range funding required

   Broad support by AF, DoD and NASA

2. Technology Areas

   Cathode Technology

      Advance technology base for oxide and dispenser (higher frequency and power) cathodes

      Materials and processing studies

      Cathode test program

      Refined analysis of cathode tests

      Standard cathode

   Encapsulant Technology

      Develop reliable materials and processes

      Materials and processing and studies

      Electrical and thermal stress tests

      Standard encapsulant

3. Improved Test Techniques and Screening Procedures

      Thermal-vacuum vs ambient screening

      Gas analysis tests

      In-process manufacturing tests

4. Programmatic Issues

   Non-proprietary Technology Developments

TABLE 6.2

CURRENT TWT CAPABILITIES: SPACE SEGMENT

FREQUENCY (GHz)	PRESENT*	NEAR TERM*	FAR TERM**
20	20	40	300
40	10	20	150
60	-	-	100

*Helix slow-wave circuit

**Coupled-cavity circuit

Standardize materials, processes and components

Improved technology available to all DoD contractors

Comprehensive Specifications

Material, component and subassembly tests

Manufacturing and Q&A procedures

Documentation

Dedicated Production Line (2 Tubes/Month?)

Better in-process control

Better scheduling

c. Recommended Improvements in Life Testing Include

1. Begin life-testing phase early in development program
2. Develop accelerated and space-simulated life tests
3. Develop high-voltage power supply reliability and life tests

6.3 Solid-State Power Amplifiers

Solid-state devices offer the potential for orders-of-magnitude increase in reliability and reduction in voltage requirements over TWTAs while TWTAs will continue to surpass solid-state devices in output power and efficiency. The potential availability of both technologies at EHF affords the opportunity to employ the optimum device for the specific application. While there are medium-power requirements where solid-state and TWT amplifiers will be competitive on a one-for-one replacement basis, there are also unique applications for each. Requirements for higher power (100 watts) in a single envelope (e.g., wideband data relay users) would best be served by TWTAs, while requirements for individual power amplifiers (1 watt) on each feed or array element of a time-hopped-beam antenna (e.g., for mobile users) would best be served by solid-state devices. Consequently, parallel development efforts are recommended in both technologies.

Within solid-state technology, there are two potential devices: IMPATT diodes which will provide useful added power capability over the entire EHF band in the near term, and GaAs FETs which will provide linear amplification and ease of combining advantages over IMPATTs. Both devices warrant development at EHF; the ultimate selection will depend upon the specific frequency and application. To extend the power limitations of individual

solid-state devices, power combining techniques are required. Binary power combining can be presently implemented at EHF using available hybrids, but incurs the largest size and weight penalty and limits the number of combined devices to 16. N-way and cavity combiners offer potential advantages but require development as delineated below.

To insure that the potential improvements in reliability and life offered by solid-state technology are achieved, a comprehensive solid-state reliability program is recommended. It should be noted that many of the recommended device development efforts are contained in current or planned SD/AFAL programs, and these efforts could be expanded in the areas of reliability and life tests.

a. The recommended device developments are summarized in Table 6.3.

TABLE 6.3

RECOMMENDED SOLID-STATE DEVICE DEVELOPMENTS

FREQUENCY (GHz)	DEVICE	GOALS	
		POWER(W)	EFF(%)
20	GaAs FET	1	25
	GaAs IMPATT	5	25
40	GaAs IMPATT	2.5	20
45	GaAs IMPATT	2	17
60	GaAs IMPATT	1	15

b. The recommendations for power combiner technology are as follows:

1. Development of N-way combiners to accommodate 10-to-20 FETs with high combining efficiency at 20 GHz.

2. Development of cavity combiners from 20 to 60 GHz with emphasis on broad bandwidth and graceful degradation.

3. For spatial combining, analysis and evaluation of the effects of device degradation and failure on overall performance.

c. Recommended aspects of solid-state reliability efforts include:

1. Screening procedures to eliminate defective devices and determine failure mechanisms.

2. Test procedures to determine the operating voltage and temperature margins of devices

3. MILSPEC qualification and life testing of both devices and complete amplifiers.

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APPENDIX A

ESTIMATES OF RAIN ATTENUATION

This appendix presents global estimates of rain attenuation based on the refined rain attenuation prediction model described in Section V. The following comments apply to the data being presented:

1. The attenuation estimates include oxygen and water vapor absorption in addition to rain attenuation.

2. For each rain rate climate region, an average latitude is selected to represent that region.

3. For those cases (tropical regions and 10^{o} elevation angle) where the surface projection of the propagation path (D) exceeds 22.5 Km, the occurrence probabilities are adjusted (Eqn. 5.17) to obtain the point rain rates for the calculation.

Tabulated attenuation estimates are presented for the eight major climate regions and for frequencies of 7, 20, 30, 40, 45 and 50 GHz with elevation angle and path availability as parameters. For ease of reference, the elevation angles and path availabilities for each of the tables are as follows

Tables A1-A3: 10^{o}, 20^{o} and 30^{o} elevation angles
- A1: 91% to 99% path availability
- A2: 99.1% to 99.9%
- A3: 99.91% to 99.99%

Tables A4-A6: 45^{o}, 60^{o} and 90^{o} elevation angles
- A4: 91% to 99% path availability
- A5: 99.1% to 99.9%
- A6: 99.91% to 99.99%

TABLE A1

Estimates of Atmospheric Plus Rain Attenuation: 10°, 20° and 30° Elevation Angles; 91% to 99% Path Availability

ELEVATION ANGLE (DEG)

		10						20						30					
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
A/ 70	91.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	92.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	93.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	94.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	95.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	96.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	97.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	98.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
A/ 70	99.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	91.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	92.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	93.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	94.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	95.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	96.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	97.00%	0	1	1	2	4	11	0	1	1	1	2	5	0	1	0	1	1	4
B/ 55	98.00%	0	2	1	2	5	11	0	1	1	1	2	6	0	1	0	1	1	4
B/ 55	99.00%	0	2	2	4	7	13	0	1	1	2	3	7	0	1	1	1	2	4
C/ 50	91.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
C/ 50	92.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
C/ 50	93.00%	0	1	1	2	5	11	0	1	1	1	2	5	0	1	0	1	1	4
C/ 50	94.00%	0	2	1	2	5	11	0	1	1	1	2	5	0	1	0	1	1	4
C/ 50	95.00%	0	2	1	2	5	11	0	1	1	1	2	6	0	1	0	1	2	4
C/ 50	96.00%	0	2	2	3	5	12	0	1	1	1	2	6	0	1	1	1	2	4
C/ 50	97.00%	0	2	2	4	6	13	0	1	1	2	3	6	0	1	1	1	2	4
C/ 50	98.00%	0	2	3	5	8	15	0	1	1	2	3	7	0	1	1	1	2	4
C/ 50	99.00%	0	3	5	8	12	19	0	1	2	3	5	9	0	1	1	2	3	6

TABLE A1 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					10						20						30		
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
D/ 45	91.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
D/ 45	92.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
D/ 45	93.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
D/ 45	94.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
D/ 45	95.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
D/ 45	96.00%	0	2	2	3	6	13	0	1	1	1	3	6	0	1	1	1	2	4
D/ 45	97.00%	0	2	3	5	9	16	0	1	1	2	4	7	0	1	1	1	2	5
D/ 45	98.00%	0	3	6	9	13	21	0	1	2	4	6	10	0	1	1	2	3	5
D/ 45	99.00%	1	6	11	18	23	31	0	3	5	8	11	15	0	1	3	5	6	9
E/ 30	91.00%	0	2	1	2	5	12	0	1	1	1	2	5	0	1	0	1	1	4
E/ 30	92.00%	0	2	3	4	8	15	0	1	1	1	3	6	0	1	0	1	2	4
E/ 30	93.00%	0	3	4	7	10	18	0	1	1	2	4	7	0	1	1	1	2	5
E/ 30	94.00%	0	3	5	10	14	22	0	1	2	3	5	9	0	1	1	2	3	5
E/ 30	95.00%	0	4	7	13	18	26	0	2	3	5	7	11	0	1	2	3	4	7
E/ 30	96.00%	1	5	10	17	23	31	0	2	4	7	10	14	0	1	2	4	6	9
E/ 30	97.00%	1	7	14	24	30	40	0	3	6	10	13	18	0	2	4	6	8	11
E/ 30	98.00%	1	9	19	32	39	50	0	5	10	17	20	26	0	3	6	10	12	15
E/ 30	99.00%	1	14	31	49	58	70	1	8	17	27	32	38	0	6	12	19	22	27
F/ 35	91.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
F/ 35	92.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
F/ 35	93.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
F/ 35	94.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
F/ 35	95.00%	0	1	1	2	4	10	0	1	1	1	2	5	0	1	0	1	1	4
F/ 35	96.00%	0	2	2	3	6	12	0	1	1	1	2	6	0	1	0	1	2	4
F/ 35	97.00%	0	2	3	4	8	15	0	1	1	1	3	6	0	1	1	1	2	4
F/ 35	98.00%	0	3	4	7	11	19	0	1	1	3	4	8	0	1	1	1	2	5
F/ 35	99.00%	0	4	8	14	19	27	0	2	3	5	8	11	0	1	2	3	5	8

TABLE A1 (Cont'd)

ELEVATION ANGLE (DEG)

					10						20						30		
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
G/ 10	91.00%	0	2	2	3	6	12	0	1	1	1	2	5	0	1	0	1	1	4
G/ 10	92.00%	0	2	2	3	6	12	0	1	1	1	2	5	0	1	0	1	1	4
G/ 10	93.00%	0	2	2	3	6	12	0	1	1	1	2	5	0	1	0	1	1	4
G/ 10	94.00%	0	2	2	3	6	12	0	1	1	1	2	5	0	1	0	1	1	4
G/ 10	95.00%	0	2	2	3	6	12	0	1	1	1	2	5	0	1	0	1	1	4
G/ 10	96.00%	0	5	9	15	21	30	0	2	3	5	7	11	0	1	1	3	4	7
G/ 10	97.00%	1	7	14	23	30	40	0	3	6	16	13	18	0	2	3	5	7	10
G/ 10	98.00%	1	10	20	34	42	53	0	5	10	17	21	26	0	3	6	11	13	17
G/ 10	99.00%	1	15	34	55	65	77	1	8	18	29	35	41	1	6	13	21	24	29
H/ 0	91.00%	0	4	7	12	17	25	0	1	2	3	5	9	0	1	1	2	3	5
H/ 0	92.00%	0	5	9	16	21	30	0	2	3	5	7	11	0	1	2	3	4	7
H/ 0	93.00%	1	6	11	19	25	35	0	2	4	7	10	14	0	1	2	4	6	8
H/ 0	94.00%	1	7	13	23	30	40	0	3	5	9	12	17	0	2	3	5	7	10
H/ 0	95.00%	1	8	16	28	35	45	0	4	7	13	16	21	0	2	4	7	9	12
H/ 0	96.00%	1	9	20	34	42	52	0	5	10	16	20	25	0	3	5	9	12	15
H/ 0	97.00%	1	12	25	41	50	61	1	6	13	21	26	32	0	4	8	13	16	19
H/ 0	98.00%	1	15	34	55	65	77	1	8	18	29	35	41	1	6	13	21	24	29
H/ 0	99.00%	2	23	50	78	90	104	1	13	29	46	52	59	1	10	22	34	38	43

TABLE A2

Estimates of Atmospheric Plus Rain Attenuation: 10^{o}, 20^{o} and 30^{o} Elevation Angles; 99.1% to 99.9% Path Availability

		ELEVATION ANGLE (DEG)																	
					10						20						30.		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20.	30.	40	45.	50.
A/ 70	99.10%	0	1	1	2	4	10.	0	1.	1	1	2	5	0	1.	0.	1	1.	4.
A/ 70	99.20%	0	1	1.	2	4.	10	0	1	1	1	2.	5.	0.	1	0.	1.	1	4
A/ 70	99.30%	0	1	1.	2	4.	10	0	1	1	1.	2.	5.	0.	1	0	1.	1.	4.
A/ 70	99.40%	0	1.	1.	2	4.	11.	0.	1	1.	1.	2.	5	0.	1	0.	1.	1.	4.
A/ 70	99.50%	0	1.	1.	2	5	11.	0.	1.	1.	1.	2.	5.	0	1.	0	1.	1.	4
A/ 70	99.60%	0	2	2	2.	5.	11.	0.	1.	1	1.	3	6.	0.	1.	0.	1.	1.	4.
A/ 70	99.70%	0	2	2.	3	5.	12.	0.	1.	1.	1.	3	6.	0.	1.	0.	1.	1.	4.
A/ 70	99.80%	0	2.	2	4	7.	13.	0.	1.	1.	1.	3.	6.	0.	1.	1	1.	2.	4.
A/ 70	99.90%	0.	3.	4.	7.	10.	17	0.	1.	2	3.	5.	8.	0	1.	1	2.	3.	5.
B/ 55	99.10%	0	2.	3	5	8.	14.	0.	1.	1.	2.	4.	7	0.	1.	1	1	2.	4.
B/ 55.	99.20%	0.	2.	3.	5	8.	15.	0.	1.	1.	2	4	7	0	1.	1.	1	2.	4.
B/ 55	99.30%	0	2.	3	5.	8.	15.	0.	1.	1.	2.	4.	7	0	1.	1.	1	2.	4.
B/ 55	99.40%	0.	3	4	6.	10.	17.	0.	1.	1.	2.	4.	7.	0.	1.	1.	1.	2.	5.
B/ 55	99.50%	0.	3	4	7.	10.	17.	0.	1.	2.	3	4.	8	0.	1	1	1	2	5.
B/ 55	99.60%	0	3.	5	9.	13.	20.	0.	1.	2.	4.	6.	9.	0	1	1	2.	4.	6.
B/ 55	99.70%	0	4	6	10.	14.	21.	0.	2	3.	4	6.	10	0	1.	2	3.	4.	6.
B/ 55	99.80%	1	5	9.	14	18.	26	0.	2.	3.	6	8.	11.	0.	1.	2	3.	5.	7.
B/ 55	99.90%	1	7	14	23	29	37.	0	3.	6	10.	13.	17	0	2	4	7.	9.	12.
C/ 50	99.10%	0	3	5	8.	12	19.	0.	1.	2	4	5.	9.	0.	1.	1.	2.	3.	6.
C/ 50	99.20%	0	3	6.	10.	14.	21.	0	1	2.	4	6	9.	0	1.	1.	2.	3.	6.
C/ 50.	99.30%	0	4.	6.	11.	15	22	0	2.	2	4.	6.	10.	0.	1.	1	2	4.	6.
C/ 50.	99.40%	0.	4	7	11	15	23	0.	2	3.	6.	8.	11.	0.	1.	2.	3	4.	6.
C/ 50.	99.50%	1	4	8	14	18	26.	0	2	4	6	8.	12	0	1	2	3.	4.	7.
C/ 50.	99.60%	1	5.	9	15	19	27.	0	2	4.	7.	9.	13	0.	1.	3.	5	6.	9.
C/ 50	99.70%	1	6	11.	19.	24	32	0	3	5.	8	10.	14.	0	2	3.	5.	7.	10.
C/ 50.	99.80%	1	7	15.	24.	30	38	0.	4.	7	12.	15.	19.	0.	2.	4.	7.	8.	11.
C/ 50.	99.90%	1.	11.	23.	37.	44.	53.	1.	6.	12.	19.	23.	28.	0.	4.	8.	13.	15.	18.

TABLE A2 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					10						20						30.		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
D/ 45	99.10%	1	6	12	19	24	32.	0.	3	5	9	11	16	0	2.	3	5.	6.	9
D/ 45	99 20%	1	6	12	20	25	34	0	3	6	10	12	16	0	2.	3	5	7.	10.
D/ 45	99 30%	1	7	13	22	27	35	0.	3	6	10	13	17	0.	2	4	6.	8	10.
D/ 45	99 40%	1	8	16	25	31.	40	0	4	7	11	14	19	0	2	4.	7	8.	11
D/ 45	99 50%	1	8.	17.	28	34	43	0	4	8	13	16	20	0.	3	6.	10	12	15
D/ 45	99 60%	1	10	21.	33	40	49	0	5.	11	17	20	25.	0	[illegible]	7.	11	13	16
D/ 45	99 70%	1	11	24	37	44	54	1.	6	12.	20	23	28.	0.	4	8	13.	15	18
D/ 45	99.80%	1	14	30	47	54	64	1	7	15	24	27	32	0.	5	10	16	18.	22.
D/ 45	99 90%	2	21.	45	68.	77	88	1.	11	25.	37	42	47	1	8.	18	28.	31	35
E/ 30	99 10%	1.	15	32	52	61	72.	1.	8.	18.	29	34	40.	1	6.	13	21.	24.	28
E/ 30	99 20%	1	16	36.	57.	67	78	1.	9.	20	31	36	42.	1	6	14.	22.	26	30.
E/ 30	99 30%	2	18	38.	60	70	82.	1	10.	21	33	38	45.	1	7	15.	24.	28	32.
E/ 30	99 40%	2	19	41	64	74	87	1	11.	23.	36.	42	48.	1	8	17.	27.	30	35.
E/ 30	99 50%	2	20	44.	69	80.	92	1	13	29	44	50	57	1	9	19	30.	33	38
E/ 30	99 60%	2	23	51	79	90	103	1	15	32	49.	55	62	1	10	22	33.	37	42
E/ 30	99.70%	2	26	58	89	100	113.	2	17	38	57	63	70	1	12	26.	39	43.	48.
E/ 30	99 80%	3	33	72	109.	121	135	2	21	47	70.	76	84.	2	17	38	56	61	66.
E/ 30	99 90%	5	47	104	153.	166	181	3	34	74	107	114	122	3.	26.	57	82	87	92.
F/ 35	99.10%	0	5	9	15	20	28	0	2	3	6.	8	12	0.	1	2.	4	5.	8
F/ 35.	99 20%	1	5	9.	16.	21	30	0	2	4	7.	9.	14	0	1	2.	4.	6.	8
F/ 35.	99 30%	1	5	10	18.	23.	32.	0	2.	4	7	10	14	0.	1	3	4.	6	9
F/ 35.	99 40%	1.	6	11	19	25	34	0.	2	5.	8.	11.	15.	0.	2.	3.	5	7.	10.
F/ 35	99 50%	1.	6.	12.	21	27	36.	0	3	5	9	12	17.	0	2.	3.	6.	7.	10.
F/ 35.	99.60%	1.	7	15.	25.	31	41.	0	3	6	11.	14	18.	0.	2	4.	6.	8.	12.
F/ 35.	99 70%	1	8	17.	28.	35	45	0	4	7.	13	16.	21.	0.	2.	5.	8.	10.	13.
F/ 35.	99.80%	1.	10	21.	35.	43.	53.	0.	5	11.	17.	21.	26.	0.	3.	7.	12.	14.	18.
F/ 35.	99 90%	1.	14.	29.	48.	56.	68	1.	7.	15.	25.	29.	35.	0.	5.	11.	17.	20.	24.

TABLE A2 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					10						20						30		
RES/LWT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40.	45	50.
G/ 10	99 10%	1	16	35	57	68	80	1	9	19	31	36	43	1	6	14.	22	26	30
G/ 10.	99 20%	1	17	37	60	71	83	1	9	21	33	38	45	1	7	15.	23.	27.	32
G/ 10	99 30%	2	18	39	63	74	87	1	10	22.	33	41.	47.	1.	7.	16	25.	29.	34.
G/ 10	99 40%	2	19	42	67	78	91.	1	11	24	38	43	50	1	8	17.	27.	31.	36.
G/ 10	99 50%	2	20	45	71.	83	96	1	12.	26	41.	47	54	1.	9.	19.	30.	34.	39.
G/ 10	99 60%	2	22	49	78	89	103.	1	13	29	45	51	59	1	10.	21	33	38.	43.
G/ 10	99 70%	2	26.	57	89	102	116	1	15	33	51	58	65	1	11.	25	38.	43.	48.
G/ 10	99 80%	3	30	67	103	117	131.	2	18	40	61	68.	75	1	14.	31	47.	52.	57.
G/ 10	99 90%	4	39	87	131.	145.	160	2	26	58	86	94.	102	2	19.	43	63.	68.	74.
H/ 0	99 10%	2	24	52	82	94	108.	1	14	31	48.	55	62	1.	11.	23.	36	40.	46.
H/ 0	99 20%	2	25	55	86	98.	112	1.	15	33	51	58	65.	1	11.	25.	38.	43.	48.
H/ 0	99 30%	2	27	59	91	103.	118	1.	16	36	55.	62.	69	1.	12.	27.	41.	46.	52.
H/ 0	99 40%	3	29	63	97	110	124	2	18	39.	60.	66	74	1	14	30	45.	50.	56.
H/ 0	99 50%	3.	32	69	105	118	133.	2	20	43	65.	72.	80	1.	15	34.	50.	55.	61.
H/ 0	99 60%	3	35	77	117	130	145.	2	22	49	74	81	89	2	17.	39.	57.	63.	68.
H/ 0	99 70%	4	42	92	138	152	167	2	26	53.	86.	93.	101	2	21.	46	68	73.	79.
H/ 0	99 80%	5	50	111	164	179	195.	3	33	72	104.	112	120	3.	27	59.	84.	90.	95.
H/ 0	99 90%	7.	68	151	216	230.	246.	5	49.	108	152	160	169	4	38	84	118.	122.	128.

TABLE A3

Estimates of Atmospheric Plus Rain Attenuation: 10^{o}, 20^{o} and 30^{o} Elevation Angles; 99.91% to 99.99% Path Availability

		ELEVATION ANGLE (DEG)																	
					10						20						30		
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
A/ 70	99 91%	0	3	4	7	11	17	0	1	2	3	5	8	0	1	1	2	3	5
A/ 70	99 92%	0	3	6	9	13	20	0	1	2	3	5	8	0	1	1	2	3	5
A/ 70	99 93%	0	3	6	10	13	21	0	1	2	4	5	9	0	1	1	2	3	5
A/ 70	99 94%	0	4	6	10	14	21	0	1	2	4	6	9	0	1	1	2	3	5
A/ 70	99.95%	0	4	7	11	15	23	0	2	3	4	6	10	0	1	2	4	5	8
A/ 70	99 96%	1	5	9	15	19	27	0	2	4	7	9	13	0	1	3	4	6	8
A/ 70	99 97%	1	6	11	17	21	29	0	3	5	8	10	14	0	2	3	5	6	9
A/ 70	99 98%	1	7	14	23	28	36	0	3	6	10	12	16	0	2	4	6	7	10
A/ 70	99 99%	1	10	21	33	38	47	1	5	11	17	20	24	0	4	8	12	14	17
B/ 55	99 91%	1	8	15	24	30	38	0	3	7	11	13	17	0	2	5	7	9	12
B/ 55	99 92%	1	9	18	28	34	43	0	4	9	14	17	21	0	2	5	8	10	13
B/ 55	99 93%	1	9	19	30	36	44	0	5	9	15	18	22	0	3	5	9	10	13
B/ 55	99 94%	1	10	20	31	37	47	0	5	10	16	19	24	0	3	6	9	11	14
B/ 55	99 95%	1	11	24	37	43	53	1	5	11	18	21	25	0	3	7	10	12	15
B/ 55	99 96%	1	12	26	40	47	56	1	6	13	19	23	27	0	5	10	15	18	21
B/ 55	99 97%	1	15	31	48	55	65	1	8	17	26	30	35	1	5	11	17	20	24
B/ 55	99 98%	2	18	39	59	67	77	1	9	20	31	35	40	1	6	14	21	24	27
B/ 55	99 99%	2	25	55	83	92	104	1	14	32	47	51	57	1	11	24	35	38	42
C/ 50	99 91%	1	12	24	38	45	55	1	6	13	20	24	29	0	4	8	13	16	19
C/ 50	99 92%	1	12	26	40	47	57	1	6	14	21	25	30	0	4	9	14	16	20
C/ 50	99 93%	1	13	27	42	49	59	1	7	15	23	26	31	0	5	10	15	18	21
C/ 50	99 94%	1	14	31	48	56	66	1	7	16	24	28	33	0	5	11	16	19	22
C/ 50	99 95%	1	15	33	51	59	69	1	8	17	26	30	35	1	5	12	18	20	24
C/ 50	99 96%	2	18	38	59	67	78	1	10	22	33	38	43	1	6	13	20	22	26
C/ 50	99 97%	2	19	42	64	72	83	1	11	25	37	41	47	1	8	18	27	31	35
C/ 50	99 98%	2	23	51	77	86	98	1	15	33	50	55	61	1	10	22	33	36	40
C/ 50	99 99%	3	34	75	110	120	133	2	21	46	67	72	79	2	17	38	55	59	63

TABLE A3 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					10						20						30.		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7.	20	30	40.	45.	50
D/ 45	99 91%	2	21	47	71	80	91	1	12	26	39	44	49	1	9	19	29.	32	36.
D/ 45	99 92%	2	22	49	74	83	94	1	13	28	41	46	52	1	9	21	31	34.	38.
D/ 45	99 93%	2	23	51	77.	86	98.	1.	15	33	50.	55	61	1	10.	22	33	36.	40
D/ 45	99.94%	2	26	57	86	96	108.	2	16	36	53.	58	64.	1	11.	24	35	38.	43.
D/ 45	99 95%	3	28	61	91	101	113	2	18	39	57	62	68.	1	12	26.	38	42.	46
D/ 45	99 96%	3	32	69.	103	113	126	2	19	42	62	67	73	1	13.	29.	42	45	49.
D/ 45	99 97%	3	34	75	111	121	134	2	24	53.	76	82	89.	2.	18	39.	56.	60	64
D/ 45	99 98%	4	40	89	129	140	153	3	28	61	87	93	100.	2	21	46	65	69	73.
D/ 45	99 99%	5	54	118.	169	181	194	4	39	86	120	126	133	3.	32	69.	96	100	105.
E/ 30	99 91%	5	49	109	159	172	187	3	35	78	111	119	127.	3	28.	61.	86.	91	96
E/ 30	99 92%	5	52	114	166.	179	194	4	37	82	117	124	132.	3	29.	64	90.	95	100
E/ 30	99 93%	5	54	120	173	187	202	4	39	87.	123	130	138.	3	31	68	95.	100	106
E/ 30	99 94%	6	58	127.	182	196	211	4	42	92	130	137	145.	3	33	73	101	106	111
E/ 30	99 95%	6	64	140.	201	215	230	5	45	98	138	145	153.	4.	36	78	109	112	118
E/ 30	99 96%	7	69	151.	215	228	244.	5	48	106	148.	155	162	4.	39.	85.	117	122	127
E/ 30	99 97%	8	75	165	233.	246	261	6	57	126	174	181	189.	5.	43.	94	129	133.	138
E/ 30	99 98%	9	87	192	268	281	296.	7	64	141	193	199	206.	6.	55.	120.	162	166	171
E/ 30	99 99%	11.	106	233	320	332	347.	8	75	163	221.	226	233.	7.	65	142.	189	192	196.
F/ 35	99 91%	1	14	31.	49.	58	70	1	7	16	26	30	36	0.	5.	11.	18	21.	25.
F/ 35.	99 92%	1	15	32	51	61	72	1	9	19	30	35	41.	1.	6.	12	19.	23.	27
F/ 35.	99 93%	1	16	35	56	66	78.	1	9	20	32	37	43	1	6.	13	21.	24.	28.
F/ 35	99 94%	2	17	37	59	69.	81	1	10	22	34	39	46.	1	7	14.	22.	26.	30
F/ 35	99 95%	2	18.	40	63.	73	85	1	11	24	37.	42	49	1.	7.	16.	25.	28.	32
F/ 35	99.96%	2	20	43	68	78	91	1	12	26	41	46	53	1.	8.	18.	27	31.	35.
F/ 35	99.97%	2.	23.	50.	78.	89	102.	1	14	30	46.	52	59	1.	11.	23	36.	40.	45.
F/ 35.	99.98%	3.	28.	61.	94.	106	120.	2	18	39	60	66	74.	1.	13.	30.	43.	48.	53.
F/ 35.	99.99%	3.	38.	83.	124.	138	152.	2.	24.	53	79.	86.	93.	2.	18.	40.	59.	64.	66.

TABLE A3 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					10						20						30		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20.	30	40	45	50
G/ 10	99 91%	4	41	90	136	150	165	3	27	60	89	97.	106.	2	20	45	66.	71	77
G/ 10	99 92%	4	44	98	146.	161	177	3	29	63	93.	101.	110	2	21	47	69.	74.	80
G/ 10.	99.93%	4	46	102	152	167	183	3	30	67	98.	106.	114.	2	23	50	73.	78	84.
G/ 10	99 94%	5	49	108	160	174	191	3	32	71	103	111	120.	2	24	53	77.	83.	88.
G/ 10	99 95%	5.	52	114	169	184.	200.	3.	34	75	110	118	126	3	26.	57	82.	88.	94.
G/ 10	99 96%	5	55.	122	179	194	211	4	37	81	117	125	134	3	28	62	89.	94	100.
G/ 10	99 97%	6.	60	133	194	209.	225.	4	40.	89	127.	136	144	3	31.	69.	97.	103.	109.
G/ 10	99 98%	7	68.	149	215	229	246.	5.	46.	101.	142	150	159	4	40.	87	122	128	134.
G/ 10.	99 99%	9	84	185	262	277	293	6	55	122	170	177	185.	5.	49.	108.	148.	153.	159.
H/ 0	99 91%	7.	71.	157	225.	239.	255.	5	52	113.	159	167.	175	4	41.	89	123.	128.	134.
H/ 0	99.92%	8	75	165	234	249	264	6	54	119	167.	174	183	5	43.	94.	130.	134.	140.
H/ 0	99 93%	8	79.	174	246	260	275.	6	57	126	175.	183	191	5	46	100	137	142	147
H/ 0	99 94%	9	87	191.	268	283	299	6	61	134	186	193	201	5.	49	107	146.	150.	155.
H/ 0	99 95%	10.	93.	204	285	299	314	7	66	144	198	205	213	6	53	115	156	160	165.
H/ 0	99 96%	10.	100	220	305	318	334	8	71	156	213.	219.	227	6	58.	126	169	173.	177.
H/ 0	99.97%	12	110.	241	331	344.	359	9.	79.	172	232	238.	245.	7	64.	139	186.	189.	193.
H/ 0.	99.98%	13	124.	270	368.	379.	393.	10.	89	193	259	264.	270	8	73	159	210	211.	214.
H/ 0.	99 99%	16.	147	319	428.	436	449	12	106	230.	303	305	310.	11.	98.	212	276	275.	277.

TABLE A4

Estimates of Atmospheric Plus Rain Attenuation: 45^{o}, 60^{o} and 90^{o} Elevation Angles; 91% to 99% Path Availability

		ELEVATION ANGLE (DEG)																	
					45						60						90.		
REG/LAT	AVAILABILITY	7	20	30	40	45.	50	7.	20	30	40	45.	50	7	20	30	40.	45	50.
A/ 70	91.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	92 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	93.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	94 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	95 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	96 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	97 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	98 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99 00%	0	0	0	0	1	2	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	91.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	92 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	93 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	94 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	95 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	96 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	97.00%	[illegible]	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	98 00%	[illegible]	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
B/ 55	99 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	1	1	2
C/ 50	91 00%	0	[illegible]	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	92 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	93.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	94 00%	0	0	[illegible]	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	95.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	96.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	97 00%	0	0	0	1	1	3	0	0	0	0	1	2	0	0	0	0	1	2
C/ 50	98 00%	0	0	0	1	2	3	0	0	0	1	1	3	0	0	0	1	1	2
C/ 50	99.00%	0	1	1	1	2	3	0	0	1	1	2	3	0	0	1	1	2	3

TABLE A4 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					45						60						90		
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
D/ 45	91.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	92.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	93 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	94.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	95 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	96 00%	0	0	0	1	1	3	0	0	0	0	1	2	0	0	0	0	1	2
D/ 45	97 00%	0	0	0	1	1	3	0	0	0	1	1	2	0	0	0	1	1	2
D/ 45	98.00%	0	1	1	2	2	4	0	0	1	1	1	3	0	0	1	1	2	3
D/ 45	99.00%	0	1	2	3	4	6	0	1	1	2	3	5	0	1	1	2	3	4
E/ 30	91.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
E/ 30	92.00%	0	0	0	1	1	3	0	0	0	0	1	2	0	0	0	0	1	2
E/ 30	93.00%	0	0	0	1	1	3	0	0	0	0	1	2	0	0	0	0	1	2
E/ 30	94 00%	0	0	1	1	2	3	0	0	0	1	1	3	0	0	0	1	1	2
E/ 30	95.00%	0	1	1	1	2	4	0	0	1	1	2	3	0	0	0	1	1	3
E/ 30	96 00%	0	1	1	2	3	5	0	1	1	1	2	4	0	0	1	1	2	3
E/ 30	97 00%	0	1	2	3	5	7	0	1	1	2	3	5	0	1	1	2	3	4
E/ 30	98 00%	0	2	3	6	7	10	0	1	2	4	5	7	0	1	2	4	5	6
C/ 30	99.00%	0	4	8	13	15	18	0	3	6	9	11	13	0	2	4	7	9	11
F/ 35	91.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	92.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	93 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	94 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	95.00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	96 00%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	97.00%	0	0	0	1	1	3	0	0	0	0	1	2	0	0	0	0	1	2
F/ 35	98.00%	0	0	0	1	2	3	0	0	0	1	1	2	0	0	0	0	1	2
F/ 35	99.00%	0	1	1	2	3	5	0	0	1	1	2	3	0	0	1	1	2	3

TABLE A4 (Cont'd)

		ELEVATION ANGLE (DEG)																	
					45.						60.						90.		
PEG/LAT	AVAILABILITY	7	20	30	40	45.	50	7	20	30.	40.	45	50.	7.	20	30.	40.	45.	50.
G/ 10	91 00%	0	0.	0.	0.	1.	3	0	0.	0.	0.	1.	2.	0	0	0	0.	1.	2
G/ 10	92.00%	0.	0.	0	0	1.	3.	0.	0	0.	0.	1.	2	0	0.	0.	0.	1.	2.
G/ 10	93.00%	0	0	0	0.	1.	3.	0.	0.	0.	0.	1.	2.	0.	0.	0.	0.	1.	2.
G/ 10	94 00%	0	0.	0.	0.	1.	3.	0.	0.	0.	0.	1.	2.	0.	0.	0.	0.	1.	2.
G/ 10	95.00%	0	0.	0.	0.	1.	3.	0.	0.	0.	0.	1.	2.	0.	0.	0.	0.	1.	2.
G/ 10	96 00%	0.	1.	1.	2	2.	4.	0.	0.	1.	1.	2.	3.	0	0.	0	1.	1.	2.
G/ 10	97.00%	0.	1.	2	3.	5.	7.	0.	1.	1.	2.	3.	5.	0	0.	1.	1.	2.	4.
G/ 10	98.00%	0.	2.	4	6.	8.	11.	0.	1.	3.	4.	6.	8.	0.	1.	2	3.	4.	6.
G/ 10	99 00%	0	4.	8	13.	15.	19.	0.	3.	6.	10.	12.	14.	0.	2.	4.	7.	9.	11.
H/ 0	91 00%	0.	0.	1	1.	2.	3.	0.	0.	0.	1.	1.	3	0.	0.	0	0	1.	2.
H/ 0.	92.00%	0.	1.	1	2.	2.	4.	0.	0.	1.	1.	2.	3	0.	0.	0.	1.	1.	2.
H/ 0	93 00%	0	1.	1	2.	3.	5.	0.	1.	1.	2.	2.	4	0.	0.	1.	1.	2.	3.
H/ 0	94 00%	0.	1	2	3.	4.	7.	0.	1.	1.	2.	3.	5	0.	0.	1.	1.	2.	4.
H/ 0	95.00%	0	1	3.	4.	6.	8.	0	1.	2	3.	4.	6.	0.	1.	1.	2	3.	4.
H/ 0	96.00%	0	2	4.	6	8.	10.	0.	1.	2	4.	6.	8.	0.	1.	2.	3.	4.	6.
H/ 0.	97 00%	0.	2.	5.	9.	11.	13.	0.	2.	4	6.	8.	10.	0.	1.	3.	4.	6.	7.
H/ 0	98.00%	0	4.	8	13.	16.	19	0.	3.	6.	10.	12.	14.	0.	2.	4.	7	9.	11.
H/ 0.	99.90%	1	7.	15.	23.	26.	29	0	5.	12.	18.	21.	24.	0.	4.	9.	14.	16	18.

TABLE A5

Estimates of Atmospheric Plus Rain Attenuation: 45^{o}, 60^{o} and 90^{o} Elevation Angles; 91.9% to 99.9% Path Availability

		ELEVATION ANGLE (DEG)																	
					45						60						90		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
A/ 70	99.10%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.20%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.30%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.40%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.50%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.60%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.70%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	0	1	2
A/ 70	99.80%	0	0	0	0	1	3	0	0	0	0	1	2	0	0	0	1	1	2
A/ 70	99.90%	0	1	1	1	2	4	0	0	0	0	1	2	0	0	1	1	1	3
B/ 55	99.10%	0	0	1	1	2	3	0	0	0	0	1	2	0	0	0	1	1	2
B/ 55	99.20%	0	0	1	1	2	3	0	0	0	0	1	2	0	0	0	1	1	2
B/ 55	99.30%	0	0	1	1	2	3	0	0	0	0	1	2	0	0	0	1	1	2
B/ 55	99.40%	0	0	1	1	2	3	0	0	1	1	2	3	0	0	0	1	1	3
B/ 55	99.50%	0	1	1	1	2	3	0	0	1	1	2	3	0	0	1	1	1	3
B/ 55	99.60%	0	1	1	1	2	4	0	0	1	1	2	3	0	0	1	1	2	3
B/ 55	99.70%	0	1	1	1	2	4	0	1	1	1	2	3	0	0	1	1	2	3
B/ 55	99.80%	0	1	1	2	2	4	0	1	1	2	2	4	0	1	1	2	2	4
B/ 55	99.90%	0	1	3	4	5	7	0	1	1	2	3	4	0	1	2	3	4	5
C/ 50	99.10%	0	1	1	1	2	4	0	0	1	1	2	3	0	0	1	1	2	3
C/ 50	99.20%	0	1	1	1	2	4	0	0	1	1	2	3	0	0	1	1	2	3
C/ 50	99.30%	0	1	1	1	2	4	0	0	1	1	2	3	0	0	1	1	2	3
C/ 50	99.40%	0	1	1	1	2	4	0	0	1	1	2	3	0	1	1	1	2	3
C/ 50	99.50%	0	1	1	2	3	5	0	1	1	1	2	3	0	1	1	2	2	4
C/ 50	99.60%	0	1	2	3	4	6	0	1	1	1	2	4	0	1	1	2	3	4
C/ 50	99.70%	0	1	2	3	4	6	0	1	1	2	2	4	0	1	1	2	3	4
C/ 50	99.80%	0	1	2	4	5	7	0	1	2	4	5	6	0	1	2	3	4	5
C/ 50	99.90%	0	2	4	6	7	9	0	2	3	5	7	8	0	2	3	5	5	8

TABLE A5 (Cont'd)

		ELEVATION ANGLE (DEG)																	
		45						60						90					
REG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
D/ 45	99.10%	0	1	2	3	4	5	0	1	2	3	4	5	0	1	1	2	3	4
D/ 45	99.20%	0	1	2	3	4	6	0	1	2	3	4	5	0	1	1	2	3	5
D/ 45	99.30%	0	1	2	4	5	7	0	1	2	3	4	6	0	1	2	3	4	5
D/ 45	99.40%	0	1	2	4	5	7	0	1	2	4	5	6	0	1	2	3	4	5
D/ 45	99.50%	0	1	3	4	6	8	0	1	2	4	5	7	0	1	2	4	5	6
D/ 45	99.60%	0	2	3	5	6	8	0	1	3	5	6	7	0	1	3	4	5	7
D/ 45	99.70%	0	3	6	9	10	13	0	2	3	6	7	8	0	2	3	5	7	8
D/ 45	99.80%	0	3	7	11	13	15	0	2	4	7	8	10	0	2	5	7	9	10
D/ 45	99.90%	0	5	11	16	18	21	0	5	10	15	17	20	0	4	8	12	14	16
E/ 30	99.10%	0	4	9	14	17	19	0	3	6	10	12	14	0	2	5	8	9	11
E/ 30	99.20%	0	5	10	15	18	21	0	3	7	11	13	16	0	3	5	9	10	12
E/ 30	99.30%	0	5	11	17	19	23	0	4	8	12	14	17	0	3	6	10	11	14
E/ 30	99.40%	1	6	12	19	21	25	0	4	9	14	16	19	0	3	7	11	13	15
E/ 30	99.50%	1	6	14	21	24	27	0	5	10	16	18	21	0	4	8	13	15	17
E/ 30	99.60%	1	7	16	24	27	31	1	6	12	19	21	24	0	5	10	16	18	20
E/ 30	99.70%	1	9	19	29	32	35	1	7	15	23	25	28	1	6	13	19	22	24
E/ 30	99.80%	1	12	25	37	40	44	1	9	20	30	32	35	1	8	18	27	29	32
E/ 30	99.90%	2	18	40	56	59	63	2	15	33	47	49	52	1	15	33	46	49	51
F/ 35	99.10%	0	1	1	2	3	5	0	0	1	1	2	4	0	0	1	1	2	3
F/ 35	99.20%	0	1	1	2	3	5	0	1	1	1	2	4	0	0	1	1	2	3
F/ 35	99.30%	0	1	1	2	3	5	0	1	1	2	2	4	0	0	1	1	2	3
F/ 35	99.40%	0	1	2	3	4	6	0	1	1	2	3	4	0	1	1	2	2	4
F/ 35	99.50%	0	1	2	3	4	6	0	1	1	2	3	4	0	1	1	2	3	4
F/ 35	99.60%	0	1	2	4	5	7	0	1	1	2	3	5	0	1	1	2	3	4
F/ 35	99.70%	0	1	3	5	6	8	0	1	2	3	4	6	0	1	2	3	4	5
F/ 35	99.80%	0	2	4	6	8	10	0	2	3	5	7	9	0	1	2	4	5	7
F/ 35	99.90%	0	3	7	12	14	17	0	2	5	8	10	12	0	2	4	6	8	10

TABLE A5 (Cont'd)

		<<<<ELEVATION ANGLE (DEG)																	
					45						60						90		
PEG/LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
G/ 10	99.10%	0	4	9	14	17	20	0	3	7	11	13	15	0	2	5	8	9	11
G/ 10	99.20%	0	4	10	15	18	21	0	3	7	12	14	16	0	2	5	9	10	12
G/ 10	99.30%	0	5	10	17	19	22	0	4	8	13	15	17	0	3	6	9	11	13
G/ 10	99.40%	0	5	11	18	21	24	0	4	9	14	16	19	0	3	6	10	12	15
G/ 10	99.50%	1	6	13	20	23	26	0	5	10	16	18	21	0	3	7	12	14	16
G/ 10	99.60%	1	7	15	23	26	29	0	5	12	18	20	23	0	4	9	14	16	18
G/ 10	99.70%	1	8	17	27	30	33	1	6	14	21	24	27	0	5	11	17	19	22
G/ 10	99.80%	1	10	22	33	36	40	1	8	18	27	30	33	1	7	15	22	25	27
G/ 10	99.90%	1	14	31	46	49	53	1	12	27	39	42	45	1	10	23	34	37	40
H/ 0	99.10%	1	7	16	25	28	31	1	6	13	20	22	25	0	4	10	15	17	20
H/ 0	99.20%	1	8	17	27	30	33	1	6	14	21	24	27	0	5	11	17	19	21
H/ 0	99.30%	1	9	19	29	32	36	1	7	15	23	26	29	0	5	12	18	21	23
H/ 0	99.40%	1	10	21	32	35	39	1	8	17	26	29	32	1	6	14	21	23	26
H/ 0	99.50%	1	11	24	36	39	43	1	9	20	30	32	36	1	7	16	24	26	29
H/ 0	99.60%	1	13	28	41	45	49	1	11	23	35	38	41	1	9	19	29	31	34
H/ 0	99.70%	1	15	34	49	53	57	1	13	29	42	45	48	1	11	25	36	39	42
H/ 0	99.80%	2	20	44	62	66	70	2	17	38	54	57	61	2	16	34	49	52	55
H/ 0	99.90%	3	30	65	90	93	97	3	27	59	80	83	86	3	26	57	78	80	83

TABLE A6

Estimates of Atmospheric Plus Rain Attenuation: 45^{o}, 60^{o} and 90^{o} Elevation Angles; 99.91% to 99.99% Path Availability

		ELEVATION ANGLE (DEG)																	
					45						60						90		
REG. LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
A/ 70	99.91%	0	1	1	1	2	4	0	0	0	0	1	2	0	0	1	1	2	3
A/ 70	99.92%	0	1	1	1	2	4	0	1	1	1	2	3	0	0	1	1	2	3
A/ 70	99.93%	0	1	1	2	2	4	0	1	1	1	2	4	0	0	1	1	2	3
A/ 70	99.94%	0	1	1	2	2	4	0	1	1	2	2	4	0	1	1	1	2	3
A/ 70	99.95%	0	1	1	2	3	4	0	1	1	2	2	4	0	1	1	2	2	4
A/ 70	99.96%	0	1	1	2	3	5	0	1	1	2	3	4	0	1	1	2	3	4
A/ 70	99.97%	0	1	1	2	3	5	0	1	1	2	3	4	0	1	1	2	3	4
A/ 70	99.98%	0	1	2	3	4	6	0	1	2	3	4	5	0	1	2	3	4	5
A/ 70	99.99%	0	2	5	8	9	11	0	1	2	4	5	6	0	2	3	5	6	8
B/ 55	99.91%	0	1	3	5	6	8	0	1	1	2	3	5	0	1	2	3	4	6
B/ 55	99.92%	0	2	3	5	6	8	0	1	3	4	6	7	0	1	2	4	5	6
B/ 55	99.93%	0	2	3	5	6	9	0	1	3	5	6	8	0	1	2	4	5	6
B/ 55	99.94%	0	2	4	6	7	9	0	2	3	5	6	8	0	1	3	5	6	7
B/ 55	99.95%	0	2	4	6	8	10	0	2	4	6	7	9	0	2	3	5	6	8
B/ 55	99.96%	0	2	5	7	9	11	0	2	4	7	8	10	0	2	4	6	7	9
B/ 55	99.97%	0	4	8	12	14	17	0	2	5	8	9	11	0	2	5	8	9	11
B/ 55	99.98%	0	5	10	15	17	20	0	3	6	10	11	13	0	3	7	10	12	13
B/ 55	99.99%	1	7	14	21	23	26	1	6	14	20	22	25	0	5	11	16	18	20
C/ 50	99.91%	0	3	6	9	11	13	0	2	4	6	7	9	0	2	3	6	7	8
C/ 50	99.92%	0	3	6	10	11	14	0	2	4	6	7	9	0	2	4	6	7	9
C/ 50	99.93%	0	3	7	11	12	15	0	2	4	7	8	10	0	2	4	7	8	10
C/ 50	99.94%	0	3	7	12	13	16	0	2	5	7	8	10	0	2	5	8	9	11
C/ 50	99.95%	0	4	8	13	15	17	0	2	5	8	9	11	0	3	6	9	10	12
C/ 50	99.96%	0	4	9	14	16	19	0	3	6	9	10	12	0	3	6	10	11	13
C/ 50	99.97%	0	5	11	16	18	21	0	3	7	10	12	14	0	4	8	12	14	16
C/ 50	99.98%	1	6	13	20	22	25	1	6	13	19	21	23	0	5	11	16	18	20
C/ 50	99.99%	1	12	27	38	41	44	1	9	20	25	31	33	1	9	19	27	29	31

TABLE A6 (Cont'd)

ELEVATION ANGLE (DEG)

					45						60						90		
REG LAT	AVAILABILITY	7	20	30	40	45	50	7	20	30	40	45	50	7	20	30	40	45	50
D 45	99 91%	1	5	12	17	19	22	0	5	11	16	18	21	0	4	9	13	15	17
D 45	99 92%	1	6	12	19	21	23	1	5	12	18	19	22	0	4	10	15	16	18
D 45	99 93%	1	6	13	20	22	25	1	6	13	19	21	23	0	5	11	16	18	20
D 45	99 94%	1	7	15	22	24	26	1	6	14	21	23	25	1	6	12	18	20	22
D 45	99 95%	1	10	21	31	34	37	1	7	16	23	25	27	1	6	14	20	22	24
D 45	99 96%	1	11	24	35	37	40	1	8	18	25	27	30	1	7	16	23	25	28
D 45	99 97%	1	12	27	39	42	45	1	9	20	29	31	34	1	9	20	28	30	32
D 45	99 98%	2	15	33	46	49	52	1	11	25	35	37	39	1	12	25	36	38	40
D 45	99 99%	2	20	44	60	63	66	2	21	46	63	65	68	2	18	39	54	56	58
E 30	99 91%	2	19	42	59	62	66	2	16	35	49	52	55	2	16	35	50	52	55
E 30	99 92%	2	20	45	63	66	69	2	17	38	52	55	58	2	17	38	54	56	59
E 30	99 93%	3	26	57	80	83	87	2	18	40	56	58	61	2	19	42	58	61	63
E 30	99 94%	3	28	62	85	89	92	2	20	44	60	62	65	2	21	46	64	66	69
E 30	99 95%	3	31	67	92	95	99	3	27	60	82	84	87	3	24	52	71	73	76
E 30	99 96%	4	34	74	100	103	107	3	30	66	89	92	94	3	27	59	80	82	84
E 30	99 97%	4	38	82	111	113	117	4	34	74	100	102	104	4	32	69	93	94	96
E 30	99 98%	5	43	94	126	128	130	4	40	86	114	115	117	4	39	84	111	112	114
E 30	99 99%	6	52	113	149	150	152	6	48	105	137	137	138	6	52	112	145	144	144
F 35	99 91%	0	4	8	12	15	18	0	3	6	9	11	13	0	2	4	7	8	10
F 35	99 92%	0	4	8	13	16	19	0	3	6	10	11	14	0	2	5	8	9	11
F 35	99 93%	0	4	9	14	17	20	0	3	7	12	12	15	0	2	5	8	10	12
F 35	99 94%	0	5	10	16	18	21	0	3	7	12	13	16	0	3	6	9	11	13
F 35	99 95%	0	5	11	17	20	23	0	4	8	13	15	17	0	3	7	11	12	15
F 35	99 96%	1	6	13	20	22	25	0	4	10	15	17	19	0	4	8	12	14	17
F 35	99 97%	1	7	15	23	26	29	0	5	11	18	20	22	0	4	10	15	17	20
F 35	99 98%	1	9	19	28	31	35	1	7	15	22	25	27	1	6	13	20	22	25
F 35	99 99%	1	15	33	48	51	55	1	13	28	40	43	47	1	10	22	32	35	38

TABLE A6 (Cont'd)

ELEVATION ANGLE (DEG)

PEG/LAT	AVAILABILITY	7	20	30	45 40	45	50	7	20	30	60 40	45	50	7	20	30	90 40	45	50
G/ 10	99 91%	1	15	33	48	52	56	1	13	28	41	44	47	1	11	25	36	39	42
G/ 10	99 92%	2	16	35	51	54	58	1	14	30	43	46	50	1	12	27	39	41	45
G/ 10	99 93%	2	17	37	54	57	61	1	15	32	46	49	53	1	13	29	42	44	48
G/ 10	99 94%	2	18	40	57	61	65	2	16	35	50	53	55	1	14	31	45	48	51
G/ 10	99 95%	2	20	43	61	65	69	2	17	38	54	57	60	2	16	35	50	53	56
G/ 10	99 96%	2	21	47	67	70	74	2	19	42	59	62	65	2	18	39	55	58	61
G/ 10	99 97%	3	28	61	86	90	94	2	21	47	65	68	71	2	21	45	63	66	69
G/ 10	99 98%	3	32	71	98	102	106	3	25	55	75	78	81	3	25	55	76	78	81
G/ 10	99 99%	4	41	89	121	124	128	3	32	70	94	96	99	4	34	75	101	102	105
H/ 0	99 91%	3	31	69	94	97	101	3	28	62	85	87	90	3	28	61	83	85	88
H/ 0	99 92%	4	33	72	100	103	106	3	30	66	90	92	95	3	30	66	89	91	94
H/ 0	99 93%	4	36	78	106	109	112	4	33	71	96	98	100	4	33	72	97	98	101
H/ 0	99 94%	4	38	84	113	116	119	4	35	77	103	105	107	4	36	79	106	107	109
H/ 0	99 95%	5	42	91	122	124	127	4	39	84	111	113	115	5	41	88	116	117	113
H/ 0	99 96%	5	46	100	133	135	137	5	43	93	122	123	125	5	46	100	131	131	132
H/ 0	99 97%	6	52	112	147	148	150	6	48	104	136	136	137	6	53	116	150	149	149
H/ 0.	99 98%	8	69	150	195	195	196	7	56	121	156	155	155	8	65	139	178	175	175
H/ 0	99 99%	10	85	183	235	232	232	8	69	149	189	186	185	11	85	183	229	222	220

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radio frequency spectrum	high power amplifier (HPA)
geostationary orbital arc	traveling wave tube amplifier (TWTAs)
EHF	solid state amplifiers (SSAs)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Severe crowding of the radio frequency spectrum and of the geostationary orbital arc, coupled with DoD requirements for increased bandwidth, impel the transition of future MILSATCOM systems to operating frequencies between 20 and 50 GHz (EHF). The development of the systems architecture and transitional strategy are the current focus of DCA/MSO studies. This report, prepared in support of the DCA/MSO, assesses the technology necessary to support MILSATCOM evolution to EHF.

The technology assessment delineates the current and projected availabilities of critical MILSATCOM subsystems. In addition, the equally critical issues of producibility, reliability and cost are addressed. To provide a basis for these issues, a qualitative assessment is presented of the limits, frequency dependence and implementation of EHF technology, the commercial availability of components and test equipment in these bands, and the production base at EHF. The emphasis in the subsystem assessment is directed toward the high power amplifier (HPA) which has been identified as the most costly and critical subsystem. Toward that end, traveling wave tube amplifiers (TWTAs) and solid-state amplifiers (SSAs) are assessed for both the ground and space segments. These assessments encompass potential suppliers, current commercial availability, producibility and reliability, and development efforts and projections. As rain attenuation at EHF impacts system design and technology requirements, a refined global rain attenuation model is provided. Finally, recommendations are presented for technology development efforts and further studies to support EHF MILSATCOM deployment.

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